

# **MODELING OF HEAT GENERATION IN CONCRETE**



A thesis submitted  
in Partial Fulfillment of the Requirements  
for the Degree of

**MASTER OF TECHNOLOGY**

by

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to the

**DEPARTMENT OF CIVIL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY KANPUR**

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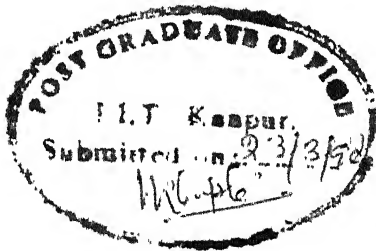
# CERTIFICATE

It is certified that the work contained in the thesis entitled "*Modeling of heat generation in mass concrete*" by **Priya Sharma**, has been carried out under my supervision and that this work has not been submitted elsewhere for the award of a degree.



Dr. Sudhir Misra  
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March, 1998



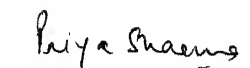
## Acknowledgement

I express my sincere thanks to my thesis supervisor, Dr. Sudhir Misra, Associate Professor in the Department of Civil Engineering, I.I.T. Kanpur, for his valuable guidance and suggestions during course of study

I am thankful to Shailesh Agarwal, Scientist at Central Building Research Institute for his timely help while my work at C.B.R.I. Roorkee.

I am greatly thankful to Groverji, Patilji and Jaswant for encouraging me and also for all those good suggestions which helped me in my work.

I am thankful to Reeta, Anuradha, Sandeep, Rakesh, Manoj, Sudip, Arun and other batchmates for making my stay at I.I.T. Kanpur memorable. I would like to thank the faculty of Structural Engineering Deptt. From whom I have learnt a lot for my future professional career. I am also thankful to my family for their constant support and encouragement.

  
Priya Sharma



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## ABSTRACT

Concrete is a composite material that consists of a binding medium within which fragments of aggregates are embedded. In most cases the binder is a mixture of cement and water. The chemical reaction between cement and water (hydration) is accompanied with liberation of large amount of heat. This work largely focuses on the modeling of the issues involved in the generation of the heat liberated during hydration of cement and the ensuing development of stresses and thermal cracks within concrete. Mineral compounds of cement clinker are focused and the heat generation of concrete is calculated based on the hydration degree of each mineral compound. In massive structures such as thick walls and dams a temperature rise occurs in hardening from the hydration process. Temperature rise in mass concrete blocks have been obtained by the heat transfer analysis using the NISA software. On account of the rise in temperature the structure strives to expand. However, restraints of different kinds prevent this expansion and tensile stresses are induced in the structure. Thermal stresses are calculated in the present work and are compared with the tensile strength of concrete to evaluate the risk of thermal crack occurrence.

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# Chapter 1

## Introduction

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### 1.1 General

Concrete can be looked upon as a composite material that consists essentially of a binding medium within which particles or fragments of aggregates are embedded. In most cases the binder is a mixture of cement and water.

The aggregate play largely passive role in the properties of fresh and/or hardened concrete. However the interaction between the water and cement (in the binder phase) is extremely dynamic and a proper understanding of this interaction at different times holds the key to a clear understanding of the properties of concrete.

The chemical reaction between cement and water is accompanied by liberation of large amounts of heat, loss in plasticity, setting and finally hardening of concrete. The movement of water within the pores of hardened concrete affecting shrinkage and creep characteristics, movement of deleterious materials e.g. chlorides, carbon-dioxide etc leading to durability related issues, etc. are some of the manifestations of the importance of the water-cement interaction.

This work largely focuses on the modeling of the issues involved in the generation (and dissipation) of the heat liberated during hydration of cement and the ensuing development of stresses and thermal cracks within concrete.

## 1.2 Hydration mechanism

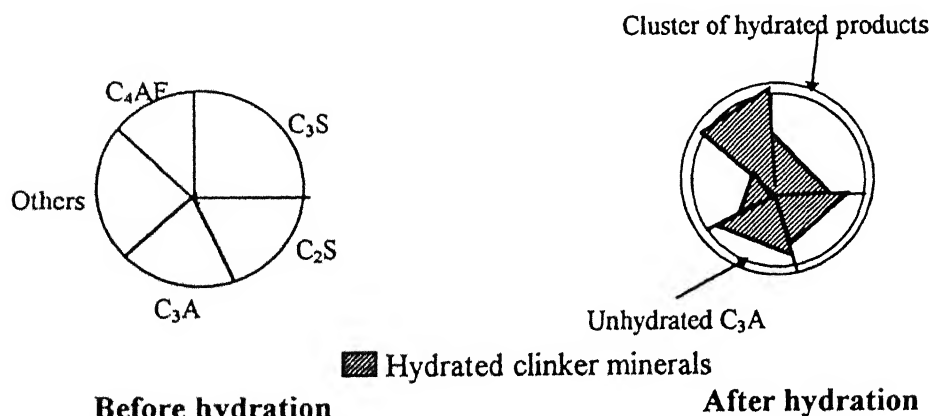
Cement is looked upon as made of several complexes e.g. Alite( $C_3S$ ), Belite( $C_2S$ ), Aluminate( $C_3A$ ), Felite( $C_4AF$ ). Typical composition of ASTM cement type 1-5 are as given in Table 1.1.

**Table 1.1 Mineral composition of the various cement types**

Mix type	$C_3S\%$	$C_2S\%$	$C_3A\%$	$C_4AF\%$
Type- 1	49	25	12	8
Type- 2	45	30	6	8
Type- 3	56	15	12	8
Type- 4	30	46	5	13
Type- 5	45	30	2	15

Each of these reacts with water resulting in the formation of new solid phases called hydrates and the corresponding reaction is termed as hydration reaction.

Figure 1.1 gives a schematic representation of the hydration process of a clinker grain.



**Fig 1.1 Schematic representation of the hydration process of a cement grain**

The progressive hydration reactions is associated with

- Decrease in free water available for further hydration
- Formation of a cluster of hydrated products around the non-hydrated particles

Free water available for hydration is a limiting factor for continuing hydration. Consumption of free water during hydration retards the further hydration.

During the hydration process, the amount of hydrated products increases. The thickness of cluster around non-hydrated particles increases which induces a barrier for hydration by introducing resistance to contact unhydrated particles with water. Thus the hydration is further retarded by increasing cluster thickness.

The reaction of cement with water forms C-S-H gel which helps in strength development, as well as is associated with liberation of considerable amount of heat.

The significance of heat of cement hydration in concrete technology is manifold. The heat of hydration can sometimes be hindrance (e.g. in mass concrete structures), and at other times a help (e.g. in winter concreting when ambient temperatures may be too low to provide the activation energy for hydration reactions).

In ordinary structural construction most of the heat generated by the hydrating cement is rapidly dissipated and only slight temperature differences develop. However, in massive structures, the combination of heat produced by cement hydration and relatively poor heat dissipation conditions results in a large rise in concrete temperature within a few days after placement. Subsequently, cooling to ambient temperature often causes the concrete to crack.

To avoid thermal cracking, the hydration heat has to be modeled as a source of temperature rise with a unified concept concerning hydration process of cement.

### **1.3 Heat of hydration**

Heat generation closely associated with temperature rise, is a direct result of hydration



of cementitious components in concrete. As the hydration proceeds each of the complexes is liberating a fixed amount of heat at a rate which can be determined by Arrhenius law.

From analysis of heat of hydration data on a large number of cements, Verback and Foster [1] computed the individual rates of heat evolution due to four principal compounds in Portland cement which are given in Table 1.2.

**Table 1.2 Heat of hydration of Portland cement compounds at different ages (cal/g)**

<i>Compound</i>	<i>3 Days</i>	<i>90 Days</i>	<i>13 Years</i>
C <sub>3</sub> S	58	104	122
C <sub>2</sub> S	12	42	59
C <sub>3</sub> A	212	311	324
C <sub>4</sub> AF	69	98	102

Since the heat of hydration of cement is an additive property, it can be predicted from an expression of the type

$$H = aA + bB + cC + dD,$$

where,

H represents the heat of hydration at a given age and under given conditions

A, B, C, D are the percentage contents of C<sub>3</sub>S, C<sub>2</sub>S, C<sub>3</sub>A and C<sub>4</sub>AF in the cement

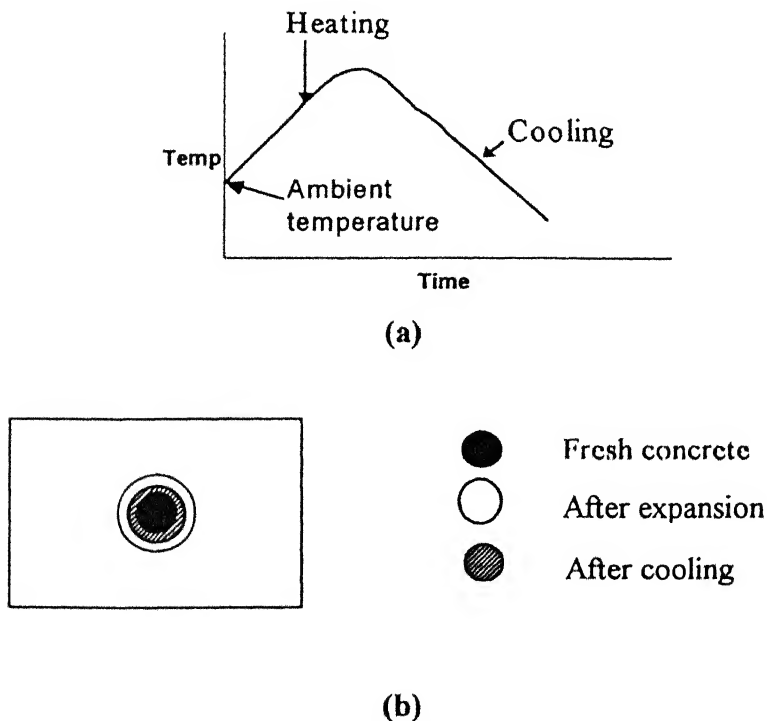
a, b, c, d are coefficients representing the contribution of 1% of the corresponding compound to the heat of hydration.

This concept is utilized to develop a wholistic model for the calculation of the heat of hydration of cement in concrete.

## 1.4 Thermal shrinkage

On account of heat developed due to hydration process and relatively poor heat dissipation conditions in mass concrete there is a large rise in concrete temperature within a few days after placement. It is well known that concrete is more or less plastic during the initial stages of hydration when the rise in temperature occurs. After a maximum temperature has been reached and cooling occurs, the concrete is stiffer and more nearly elastic. When the temperature begins to drop to the ambient temperature there is contraction which if restrained results in thermal strain thus developing thermal stresses in the structure.

If these tensile stresses exceed the value of tensile strength of concrete at that age then the result is the occurrence of thermal cracks in the structure. A simple illustration of this heating-cooling process is shown in Figure 1.2.



**Fig 1.2 Representation of heating and cooling in mass concrete**

An analysis of the factors which affect thermal stresses is given next. But before that it is essential to give the thermal properties of concrete.

### 1.4.1 Thermal properties of concrete

- *Coefficient of thermal expansion*

Coefficient of thermal expansion is defined as the change in unit length per degree of temperature change. The reported values of linear coefficient of thermal expansion for Portland cement of varying water to cement ratios, for mortars containing 1:6 cement/natural silica sand, and for concrete mixtures of different aggregate types are approximately  $18, 12, 6-12 \times 10^{-6}/^{\circ}\text{C}$ .

- *Specific heat*

Specific heat is defined as the quantity of heat needed to raise the temperature of a unit mass of a material by one degree. The specific heat of normal weight concrete is not much affected by the type of aggregate, temperature and other parameters. Typically the values of specific heat for concrete is taken as 1.05 kJ/kg.

- *Thermal conductivity*

Thermal conductivity gives the heat flux transmitted through a unit area of a material under a unit temperature gradient. The thermal conductivity of concrete is influenced by the mineralogical characteristics of aggregate, and by the moisture content, density, and temperature of concrete. Table 1.3 shows typical values of thermal conductivity for concretes containing different aggregate types.

**Table 1.3 Thermal conductivity values for concrete with different aggregate types**

<i>Aggregate type</i>	<i>Thermal conductivity (W/m.K)</i>
Quartzite	3.5
Dolomite	3.2
Limestone	2.6-3.3
Granite	2.6-2.7
Rhyolite	2.2
Basalt	1.9-2.2

- *Thermal diffusivity*

Thermal diffusivity is defined as

$$d_i = K / \rho c$$

where,

$$d_i = \text{diffusivity (m}^2\text{/hr)}$$

$$K = \text{conductivity (J/m.hr.K)}$$

$$c = \text{specific heat (J/kg.K)}$$

$$\rho = \text{density of concrete (kg/m}^3\text{)}$$

Heat will move more readily through a concrete with a higher thermal diffusivity. For normal weight concrete, the conductivity usually controls the thermal diffusivity because the density and specific heat do not vary much.

#### 1.4.2 Factors affecting thermal stresses

- *Degree of restraint*

A concrete element, if free to move would have no stress development associated with

the thermal deformation on cooling. However, in practice the concrete mass will be restrained either externally by foundation or internally by differential deformations within different areas of concrete due to presence of temperature gradients.

Thus, for the calculation of thermal stresses developed in a member it is essential to calculate the degree of restraint. The distribution of the external restraint depends on the length to height ratio of the member.

Internal restraint depends on the differential volume change within the member. Its effects add algebraically to the effects of external restraint. Where high external restraint conditions exist the effects of internal restraint may be negligible and so can be ignored.

- *Temperature change*

The hydration of cement compounds involves exothermic reactions which generates heat, and increase the temperature of concrete mass. After reaching a peak temperature the concrete mass cools down to the ambient temperature and thus there is contraction of the member which under restraint results in tensile stresses.

The maximum change in temperature can be defined as the difference between the peak temperature reached  $T_{\max}$  and service temperature  $T_s$  and can be expressed as

$$\Delta T = T_{\max} - T_s$$

- *Heat losses*

Heat losses depend on the thermal properties of concrete, geometry of the concrete blocks and the environmental conditions. Concrete can lose heat through its surface, and the magnitude of heat loss is a function of the type of environment in immediate

contact with the concrete surface. Table 1.4 shows surface transmission coefficients for different isolation environments.

**Table 1.4 Coefficients of heat transmission under different conditions**

<i>Type of isolation environment</i>	<i>Surface transmission coefficient (kcal/m<sup>2</sup>.h.C)</i>
Concrete-air	11.6
Concrete-curing water	300
Concrete-wood-air	2.6
Concrete-metal-air	11.6
Concrete-isolant-air	2.0

- *Modulus of elasticity and tensile strength of concrete*

The lower the modulus of elasticity, the lower will be the amount of the induced tensile stress. The modulus of elasticity for mass concrete can be calculated at any age depending on the compressive strength at that particular age.

The higher the tensile strength of the matrix, the lower is the risk of cracking in concrete which will occur only when the tensile stress developed exceeds the strength of the material.

Thus, thermal stresses developed on account of the heat of hydration of cement should not exceed the tensile strength of concrete at that age to avoid thermal cracking. Hence a need arises for the accurate prediction of tensile strength of concrete at any particular age. The tensile strength of concrete is influenced by factors like the type of the cement to be used, water to cement ratio, kind of aggregates, temperature history and age, and hence should be accurately predicted taken into account all of the above factors.

Though several expressions are available relating the modulus of elasticity and the tensile strength to the compressive strength, in the case of mass concrete the solidifying nature of the concrete matrix is a complicating factor. This aspect is dealt with in detail in Chapter 2.

### **1.5 Objectives of present study**

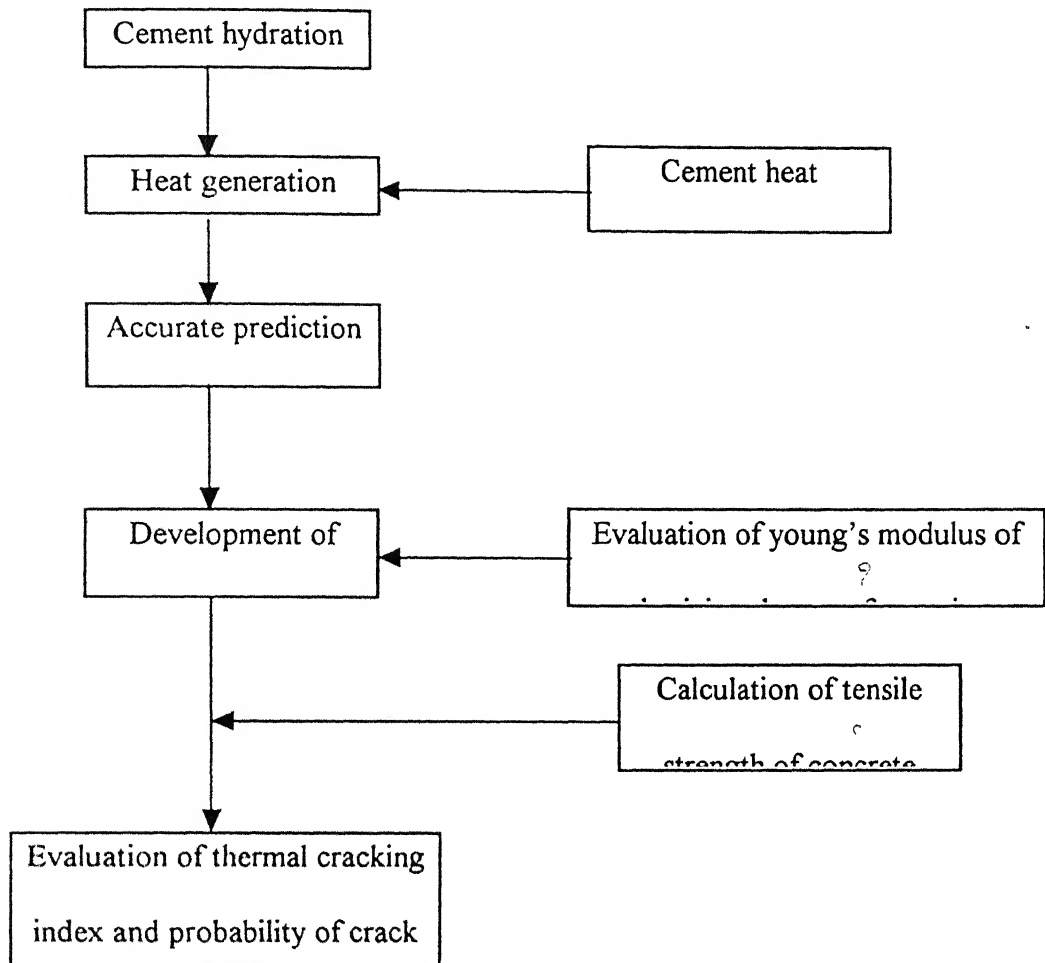
It has been clearly stated above that in case of mass concrete the heat generated due to hydration of cement can lead to thermal cracking if the thermal stresses developed are greater than the tensile strength of concrete. Thus attention is to be paid as to the design and construction practice in mass concrete so as to control thermal cracking.

An attempt has been made in this study to develop a multi-component heat generation model for the calculation of heat of hydration of cement in mass concrete. The work is further extended to the heat transfer analysis for the estimation of temperature profiles in some typical blocks as used in the dam construction using the heat of hydration as evaluated by the multi-component heat generation model.

The other parameters for calculation of thermal stresses such as modulus of elasticity, degree of restraint etc. are evaluated using the standard specifications for mass concrete.

The thermal stresses as calculated above are compared with the tensile strength of concrete at that particular age and thereby the probability of cracking is evaluated.

The flow chart of the objective of this study is given next.



**Fig 1.3 Flow chart for the objective of study**

### 1.6 Problem definition

The size of the member to be regarded as mass concrete is roughly considered to be not less than 80-100 cm in thickness for wide slabs, or to be not less than 50 cm for walls restrained at the lower end.[3]

Because concrete has low conductivity, heat generated within massive structure can escape very slowly unless measures such as pipe cooling, precooling of aggregates etc are adopted.. This heat entrapped on account of hydration of cement has to be

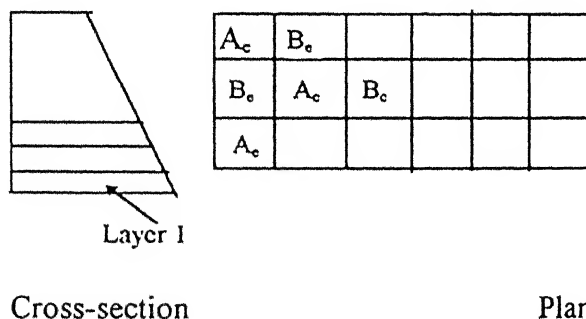


controlled in order to control thermal cracking

In a mass concrete dam the section at any level can be looked upon as a rectangular area in plan which can be cast either as

- Whole area in one stretch with thinner lift thickness, as in the case of Roller compacted concrete, OR
- Whole area can be divided into blocks which are cast alternately in subsequent rounds so as to allow quick heat dissipation.

The second method is generally adopted in case of dam construction where some time lapse is given between the first round of concreting and the next round so that overall temperature rise can be controlled. An illustration of this scheme is given in Figure 1.4.



$A_c$  Edge blocks cast in the first round of concreting

$A_c$  Central blocks cast in the first round of concreting

$B_c$  Edge blocks cast in the subsequent rounds of concreting

$B_c$  Central blocks cast in the first round of concreting

**Fig 1.4 Schematic representation of a concrete dam**

As seen from the figure A type blocks are the blocks which are cast in the first

round and B type blocks are the blocks which are cast in the subsequent rounds of concreting.

The present work includes the calculation of the heat of hydration and the heat transfer analysis of some of these typical blocks.

### **1.6.1 Calculation of heat of hydration**

The heat developed due to hydration of cement depends on the following factors:

- Type of cement
- Cement content
- Water to cement ratio
- Placing temperature

A multi-component heat generation model has been developed in the present work for the calculation of the heat of hydration which takes into account all the parameters listed above.

Portland cement is considered to be made of mineral compositions (alite, belite, aluminate, ferrite, ettringite) and the hydration heat of each of these components are modeled and summed up to get the hydration heat of Portland cement. This is the core concept of multi-component model. The concept of increasing cluster thickness and decreasing free water content during the hydration process are incorporated in the model.

### **1.6.2 Heat transfer analysis**

As explained earlier the blocks used in case of dam construction are

- Type A blocks - Blocks cast initially

- Type B blocks - Blocks cast in the subsequent rounds of concreting

The rise in temperature in concrete on account of heat of hydration depends upon

- Mix proportion
- Block size
- Placing intervals (Time interval between concreting already done and new concreting to be done in contact with the previous concrete)
- Placing temperature
- Ambient temperature
- Wind velocity
- Relative humidity

The actual rise in temperature would be naturally different in the blocks A and B because of the difference in their boundary conditions in terms of heat transfer (eg. as against air in 'A' heat would be lost to previously cast concrete blocks for 'B' blocks)

From the point of view of boundary conditions of heat transfer in these blocks, the blocks can be classified into various categories. The boundary conditions for each of these blocks for the initial and subsequent rounds of concreting is as follows:

'A' blocks:

*Foundation blocks (blocks resting on ground or foundation)*

Central blocks with conduction on one face and convection on the remaining five faces.

Edge blocks with conduction on one face and convection on the remaining five faces.

*Blocks in other layers resting on previously cast concrete*

Central blocks with conduction on two faces and convection on the remaining four faces.

Edge blocks with conduction on two faces and convection on the remaining four faces

#### 'B' blocks

*Foundation blocks (blocks resting on ground or foundation)*

Central blocks with convection on one face and conduction on the remaining five faces.

Edge blocks with convection on two faces and conduction on the remaining four faces.

*Blocks in other layers resting on previously cast concrete*

Central blocks with convection boundary condition on one face and conduction on the remaining five faces

Edge blocks with convection on two faces and conduction on the remaining four faces.

Heat transfer analysis of the blocks has been done by the finite element method using the NISA software. The heat generation rate which is used for the analysis is calculated using the multi-component heat generation model. As the heat generation rate is a function of both temperature and time Non- linear transient analysis has been carried out.

### **1.6.3 Evaluation of thermal stresses**

The following parameters have been considered for the calculation of thermal stresses :

*Temperature difference between the peak and the service temperature-* The peak temperature for the block and the time at which the peak occurs is obtained from the heat transfer analysis of the blocks.

*Degree of Restraint-* The degree of restraint is a function of the length to height ratio

of the block and is calculated using the equations given in ACI 207.2R-3.

*Modulus of elasticity*- The modulus of elasticity at any age is related to the compressive strength of concrete at that age and is calculated here using the JSCE specifications.

*Coefficient of thermal expansion*- The coefficient of thermal expansion depends on the type of aggregate and is assumed here appropriately.

Once each of the parameters listed above are calculated thermal stresses can be calculated using the relation :-

$$\sigma = K_R E \alpha (T_p - T_s)$$

where,

$K_R$  is the degree of restraint,

$E$  is the effective modulus of elasticity,

$\alpha$  is the coefficient of thermal expansion,

$T_p$  is the peak temperature and

$T_s$  is the service temperature

#### 1.6.4 Estimation of tensile strength of concrete

The tensile strength of concrete at any age is related to the compressive strength at that age and is calculated here using the equations given in the JSCE SP-2 recommendations for mass concrete structures.

#### 1.6.5 Evaluation of thermal cracking

The tensile stresses developed on account of the restrained contraction can lead to thermal cracking if these values exceed the tensile strength of concrete at that age.

As a measure of the probability of cracking a parameter called thermal cracking index is calculated which is given as the ratio of the maximum thermal stress in tension developed due to the heat of hydration and the tensile strength of concrete at that age. The relationship between the thermal cracking index and the probability of cracking is documented in the JSCE specifications based on several experiments and observation records during the actual construction.

Thus, knowing the thermal cracking index values the probability of cracking is evaluated.

## **1.7 Organisation of the study**

This thesis has been organized into 5 chapters. In chapter-1 a general introduction to the problem of thermal cracking in mass concrete, hydration mechanism of cement, factors affecting thermal shrinkage, description of thermal properties of concrete, objectives of present study and problem definition are presented.

Chapter-2 gives a brief description of the literature survey and recommendations for mass concrete as available in literature, including codes and specifications.

Chapter-3 contains in brief the description of the hydration mechanism of cement, the concept of multi-component heat generation model, model for thermal stress calculation, calculation of tensile strength of concrete and evaluation of thermal cracking.

Chapter 4 gives the discussion of the results and shows the variation in the temperature profiles and thermal stresses with different parameters like mix proportioning, placement temperature of concrete, placing interval between different

layers etc.

The conclusions obtained on the basis of the work carried out and the suggestions for further improvement are given in Chapter 5.

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## **Chapter 2**

### **Literature Survey**

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#### **2.1 General**

As is clear from Chapter 1 the heat developed due to hydration of cement in mass concrete can lead to development of tensile stresses which if greater than the tensile strength of concrete at that age can cause thermal cracking of concrete.

Thus prediction of thermal cracking in mass concrete requires

- Calculation of the heat of hydration of cement
- Accurate prediction of the rise in temperature of concrete due to this heat of hydration
- Calculation of tensile stresses developed on account of the restrained contraction
- Calculation of the tensile strength of concrete

The literature review for this study includes the review of the methodology used for the calculation of each of the above.

#### **2.2 Review of the existing models**

Various models are available in literature for the calculation of heat of hydration of cement, prediction of temperature rise, calculation of thermal stresses and evaluation of tensile strength of concrete at any age. A brief review of the models is discussed here in this section.

##### **2.2.1 Heat of hydration**

Powers and Brownyard [3] proposed models for the cement paste system on a



physical basis and brought cement and thereby concrete research a large step forward. Their models were based on a generalized description of Portland cement. The influence of the compound composition of Portland cement on the heat of hydration was dealt with by giving empirical (statistical) equations for the constants in the main models to describe the effect of the cement composition.

A more direct approach to describing the influence of the compound composition on porosity, strength and heat of hydration of Portland cement was used by Joens, Osbaeck and Parrott [4] but based on the same principle as the models by Powers and Brownyard. The modeling was based on an individual treatment of the reactions of the compounds of Portland cement. By merging the individual contributions the total changes in the cementitious system was calculated.

Woods, Steinour and Starke [5] developed the heat of solution method, for the hydration reactions in the later stages. During this period the rate of heat evolution is too low to permit the use of either the conventional adiabatic or conduction calorimeters.

Based on experimental research Rastrup [6] proposed equations for the calculation of the heat of hydration in a variable temperature process taking into account various factors like concrete mix proportion, cement type, cement content etc.

Uchida et al [7] formulated the rate of liberation of heat in cement in concrete based on the activation energy of cement hydration which was expressed as a function of cumulative heat liberation and the rate of liberation.

Suzuki et al [8] proposed a quantification technique of the hydration-heat generation process dependent on the temperature of cement in concrete and provides a general approach for deriving a hydration- heat generation model applicable to the

temperature analysis of concrete structures.

Harada et al [9] had introduced a temperature dependent heat hydration model by considering non-linear coupling analysis of heat conduction and temperature-dependent hydration of cement for the cement hydration model.

Pommersheim et al [10] had developed a mathematical model for the kinetics of hydration based on conceptual model for the hydration of tri-calcium aluminate, and the rate laws and conservation equations written for a dispersion of single-sized particle in solution. The solution is considered to be uniformly mixed and to remain isothermal.

T.Kishi and K.Maekawa [11] developed a predictive method on both heat generation and associated evolution of strength for young concrete. Mineral compounds of cement clinker and pozzolans are focused and the hydration degree of them are computed step by step with modified Arrhenius's law of chemical reaction. The specific free water and calcium hydroxide, that is an activator for pozzolans, are assigned as state variables representing chemical environment of pore solution. The strength and instantaneous stiffness of hardening concrete are related to the accumulated heat of each mineral compound and versatility of the mechanical model proposed is verified under varying temperature environments.

Berhane [12] studied about the heat generation of cement pastes under different ambient temperatures and concluded that the rate of the heat evolved is accelerated at early ages but decelerated later on.

Fernando A.Branco, Pedro A. Mendes and E.Mirambell [13] obtained the heat of hydration characteristics from experiment in which insulated concrete cubes were tested and used these characteristics to obtain the temperature and stresses.

### 2.2.2 Prediction of rise in temperature due to heat of hydration

Petti Pitkaren [14] studied the temperature fields of massive concrete structures during hardening for which the internal heat generation of concrete was based on the maturity at the particular instant. In determining the overall heat flow from the structure directed outwards the effect of convection, formwork and insulation had been taken into consideration. To determine the temperature fields during hardening the differential equation for heat conduction containing inner heat source was solved taking into account the initial and boundary conditions using the finite element method. Since in addition to time the quantity and rate of internal heat generation depend on the temperature, which is unknown in the analysis, the solution is obtained by iteration.

Fernando A.Branco, Pedro A. Mendes and E.Mirambell [13] presented a numerical method that considers environmental interaction and the concreting phases to obtain the hydration temperatures for the first few days after concreting. The heat of hydration characteristics employed in the model were obtained in the study in which insulated concrete cubes were tested.

William Cook, Buquan Miao, Pierre Claude [15] did the heat flow analysis of large columns which enabled the temperature distribution to be determined, adjusted to match the measured temperatures.

Mats Emborg, Stig Bernander [16] obtained the non-uniform temperature distribution due to heat of hydration in mass concrete from the heat transfer analysis, taking into account parameters such as type of cement and aggregate, type of concrete mixture, mix temperature, dimensions of the structure, temperature of the surrounding air etc.

Mohamed Lachemi and Pierre-Claude Aitcin [17] carried on the finite element

analysis to investigate the influence of ambient and fresh concrete temperatures on the maximum temperature and the thermal gradient in high performance concrete.

### 2.2.3 Thermal stresses

The influence of concrete strength on the thermally induced stresses during curing of large columns was investigated by William Cook, Buquan Miao, Pierre Claude [15] and Denis Mitchell. Heat flow analysis, adjusted to match the measured temperatures, enabled the temperature distribution to be determined. Finite element analysis were carried out to investigate the risk of cracking due to stresses induced by the non-linear thermal strains. The higher strength concretes did not result in larger maximum temperatures and had lower risks of cracking

Fernandez, J.A. [13] used a three dimensional finite element formulation to compute the evolution of stress distribution. The method incorporates an incremental procedure in which the temperature increase in each time increment is introduced in all nodes of the finite element mesh, and the associated stresses are computed. The magnitude of the stress distributions generated by the heat of hydration is taken to be dependent on the modulus of elasticity of concrete. This effect was considered at each step in the numerical model by computing the evolution of modulus of elasticity at early ages.

Mats Emborg and Stig Bernander [16] proposed a theoretical model for the calculation of thermal stresses assuming that the temperature is uniformly distribution and the stresses are caused by an average temperature rise. The effect of drying was neglected in their study and the structure was assumed to be surrounded by inflexible supports, i.e. the restraint is 100 percent.

### 2.2.4 Evaluation of tensile strength of concrete

T.Kishi and K.Maekawa [11] reported that bi-linear relation is seen between the strength and the entire hydration level of cement and indicated the possibility to be able to estimate the evolution of strength with the hydration degree of cement. A model was developed which is applicable to any combination of materials in which the strength is expressed in terms of the degree of hydration and the mix proportions.

F.L. Smidth [18] related the development of tensile strength of concrete to the porosity and developed a model based on the hydration reactions of cement coupled with calculations of the volumetric and thermodynamic changes associated with them including the binding of water, formation of specific hydrates, changes in porosity etc.

Raphael [19] recommends the values obtained by the splitting test of the modulus of rupture test, augmented by the multiplier found appropriate dynamic tensile test, or about 1.5.

In the present study the heat generated due to hydration is calculated using a multicomponent heat generation model and the work has been extended to thermal stress evaluation, prediction of tensile strength of concrete, calculation of Young's modulus, evaluation of thermal cracking etc. for which specifications from the various codes have been used, which are discussed here in the next section.

### 2.3 Recommendations for mass concrete from various codes

As discussed earlier prediction of thermal stresses and thermal cracking in mass concrete the following quantities are to be accurately calculated

- Young's modulus of elasticity
- Degree of restraint

- Tensile strength of concrete at any age

Different equations for the calculation of the Young's modulus, tensile strength of concrete, thermal cracking evaluation etc. are given by the different codes, some of which are discussed below

#### IS-456 1978

*Coefficient of thermal expansion-* According to IS-456 1978 the coefficient of thermal expansion depends on nature of cement, the aggregate, the cement content, the relative humidity and the size of sections. The value of coefficient of thermal expansion for concrete are tabulated with different aggregates which can be referred at best for fresh concrete.

*Tensile strength of concrete-* The flexural and split tensile strengths shall be obtained as described in IS:516-1959 and IS:5816-1970 respectively. However an estimate of the tensile strength can be made from the compressive strength using the following formula

$$f_{cr} = 0.7 \sqrt{f_{ck}} \text{ N/mm}^2 \quad (2.1)$$

where  $f_{ck}$  is the characteristic compressive strength of concrete.

*Modulus of elasticity-* The modulus of elasticity is primarily influenced by the elastic properties of the aggregates and to a lesser extent by the conditions of curing and age of the concrete, the mix proportions and the type of cement. The modulus of elasticity is normally related to the compressive strength of concrete.

In the absence of test data the modulus of elasticity may be assumed as follows:

$$E_c = 5700 \sqrt{f_{ck}} \quad (2.2)$$

where,

$E_c$  is the static modulus of elasticity in  $\text{N/mm}^2$  and

$f_{ck}$  is the characteristic cube strength of concrete in  $\text{N/mm}^2$

### ACI 207.2R-3

*Coefficient of thermal expansion*- When laboratory tests are not available, it is recommended that the thermal coefficient of expansion be assumed as  $5 \times 10^{-6}$  in./in./F for calcareous aggregate,  $6 \times 10^{-6}$  in./in./F for siliceous aggregate concrete and  $7 \times 10^{-6}$  in./in./F for quartzite aggregate.

*Tensile strength of concrete*- According to ACI 207.2R both tensile strength and ultimate tensile strain are affected by concrete aggregates such that restrained concrete of equal water cement ratios made from crushed coarse aggregate will withstand a larger drop in temperature without cracking than concrete made from rounded coarse aggregate. For a given compressive strength, however, the type of aggregate does not appreciably affect tensile strength. The age at which concrete attains its compressive strength does affect the tensile-compressive strength relationship such that the older the concrete, the larger the tensile strength for a given compressive strength.

The most commonly used test to determine the tensile strength of concrete is the splitting tensile strength. The tensile strength for normal weight concrete is usually taken as  $6.7\sqrt{f_c}$  and drying has very little effect on the relationship.

If the concrete surface has been subjected to drying, a somewhat lower tensile strength than  $6.7\sqrt{f_c}$  should be used. Where drying shrinkage has relatively less influence, a tensile strength of  $6\sqrt{f_c}$  appears reasonable. A minimum tensile strength of  $4\sqrt{f_c}$  is recommended where drying shrinkage may be considered significant.

*Modulus of elasticity*- Unless more accurate determinations are made, the elastic modulus in tension and compression may be assumed equal to  $w^{1.5}33\sqrt{f_c}$  (in psi) which

for normal weight concrete is  $57000\sqrt{f_c}$  (in psi)

*Restraint-* Two types of restraint considered in ACI-207.2R are external restraint and internal restraint.

External restraint: The distribution of the external restraint varies with the length to height ratio (L/H) of the member. the following equations are given for the calculation of the degree of external restraint.

For L/H equal to or greater than 2.5, restraint  $K_R$  can be approximated by

$$K_R = [(L/H - 2.0)(L/H + 1.0)]^{1/H} \quad (2.3)$$

For L/H less than 2.5, restraint  $K_R$  can be approximated by

$$K_R = [(L/H - 1.0)(L/H + 10.0)]^{1/H} \quad (2.4)$$

Using the degree of restraint  $K_R$  from the above equations, the tensile stress at any point can be calculated by

$$f_t = K_R \times \Delta_c \times E_c \quad (2.5)$$

where,

$K_R$  is the degree of restraint expressed as a ratio with 1.00=100 percent

$\Delta_c$  is the contraction if there were no restraint

$E_c$  is the sustained modulus of elasticity of the concrete at the time when  $\Delta_c$  occurred and for the duration involved.

*Internal restraint-* Internal restraint is similiar to the external restraint, except that the effective restraining plane is the plane of zero stress in the internal stress block and is dependent on the actual temperature gradient in the concrete. The plane of zero stress of the tensile stress block may be determined by the heat flow analysis or just by trial.

The degree of internal restraint can be approximated by the following equation-

$$K_R = 1/(1 + 2d_s W - 2d_s) \quad (2.6)$$



where,

$W$  is the total width of the slab and

$d_s$  is depth of the tensile stress block.

The effects of the internal restraint add algebraically to the effects of the external restraint, except that their summation will never exceed the effects of 100 percent external restraint. Therefore where high external restraint conditions exist the effects of internal restraint may be negligible.

### JSCE SP-2

*Thermal properties of concrete*-Thermal constants of concrete generally depend on the mix proportion of concrete, especially on such factors as the property and unit content of aggregate, and the moisture content of concrete. Therefore, the constants are recommended to be determined considering the effects of these factors. For concrete to be used in ordinary concrete structures, the thermal conductivity, specific heat and thermal diffusivity may be taken as 2.2-2.4 kcal/mh<sup>0</sup>C, 0.25-0.3 kcal/kg<sup>0</sup>C and 0.003-0.004 m<sup>2</sup>/h respectively.

*Tensile strength of concrete*- The tensile strength of concrete is influenced by factors like type of cement to be used, water cement ratio, kind of aggregates, temperature history and age.

However, to roughly predict the tensile strength using the compressive strength an approximate value may be obtained as follows-

$$f'_c(t) = [t/(a+bt)] f'_c(91) \quad (2.7)$$

$$f_t(t) = c\sqrt{f'_c(t)} \quad (2.8)$$

where,

$f_c'(t)$  is the compressive strength of concrete at an age of  $t$  days, in  $\text{kgf/cm}^2$

$f_t(t)$  is the tensile strength of concrete at an age of  $t$  days, in  $\text{kgf/cm}^2$

$f_c'(91)$  is the compressive strength of concrete at an age of 91 days, in  $\text{kgf/cm}^2$

$a$ ,  $b$  are the standard values given in table 2.1, though they vary with the type of cement.

$c$  is taken as 1.4 in standard practice, though it varies with such factors as the degree of drying of concrete.

**Table 2.1**

	a	b
High early strength Portland cement	2.9	0.97
Ordinary Portland cement	4.5	0.95
Moderate heat Portland cement	6.2	0.93

*Young's modulus*- Young's modulus of concrete of the restrained body gradually increases with age, which is also influenced by the mix proportion. The most common method to estimate the Young's modulus is to estimate the Young's modulus from compressive strength which is determined according to the integrated temperature or maturity of concrete. Following equations can be used for a simplified calculation of an approximate value-

$$E(t) = 1.1 \times 10^4 \sqrt{f_c'(t)} \quad (\text{for upto age of 3 days}) \quad (2.9)$$

$$E(t) = 1.5 \times 10^4 \sqrt{f_c'(t)} \quad (\text{for after 3 days}) \quad (2.10)$$

where

$E(t)$  is the effective Young's modulus at an age of  $t$  days, in  $\text{kgf/cm}^2$  and

$f_c'(t)$  is the estimated compressive strength of concrete at an age of  $t$  days

which can be calculated using equation 2.7.

CEB-FIP MODEL CODE 1990

*Modulus of elasticity*- In the CEB- FIP model code the modulus of elasticity of normal weight concrete can be estimated from-

$$E_c = 2.15 \times 10^4 (f_{cm}/10)^{1/3} \quad (2.11)$$

where,

$E_c$  is the 28 day modulus of elasticity of concrete (MPa) and  $f_{cm}$  the average 28-day compressive strength.

*Tensile strength*- The CEB-FIP model code recommends that the lower and upper bound values of the characteristic tensile strength,  $f_{ctk,max}$  and  $f_{ctk,min}$  may be estimated from the characteristic strength  $f_{ck}$  (in MPa units):

$$f_{ctk,min} = 0.95(f_{ck}/f_{cko})^{2/3} \text{ and } f_{ctk,max} = 1.85(f_{ck}/f_{cko})^{2/3} \quad (2.12)$$

where  $f_{cko} = 10 \text{ MPa}$

The mean value of the tensile strength is given by the relationship:

$$f_{ctm} = 1.40(f_{ck}/f_{cko})^{2/3} \quad (2.13)$$

As can be seen various theories have been proposed for the calculation of the heat of hydration of cement in concrete, prediction of thermal stresses and thermal cracking etc. In the present work a heat generation model has been used for the calculation of heat of hydration of cement in concrete and equations from JSCE and ACI have been used for the calculation of tensile strength of concrete, Young's modulus etc the details of which are presented in the next chapter.

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## Chapter 3

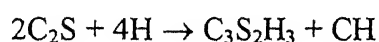
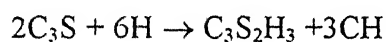
### Model Description

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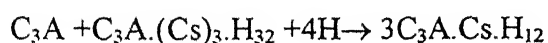
#### 3.1 Hydration mechanism

Though it is not intended to provide any detailed description and mechanisms of the hydration of cement, the various models available etc , a brief outline is presented below in so far as it is relevant to studies concerning heat of hydration.

It has already been mentioned in Chapter 1 that cement can be looked upon as made up of complexes that begin to react as soon as they come in contact with water. The solution (cement) becomes saturated with calcium hydroxide almost instantly as the tricalcium silicate present in cement passes into solution and decomposes into hydrated calcium silicate and calcium hydroxide, similarly (but to a lesser extent) dicalcium silicate also forms calcium hydroxide as given below:

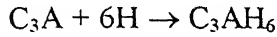


It may be noted that the rates of reaction of  $C_3S$  and  $C_2S$  are different,  $C_3S$  reacts very fast whereas the reaction of  $C_2S$  is much slower. In the hydration of aluminate components ( $C_3A$  and  $C_4AF$ ), there is vigorous participation of sulphate which derives primarily from the gypsum added to the clinker grinding. With the aid of this sulphate, tricalcium aluminate forms  $3CaO.Al_2O_3.3CaSO_4.32H_2O$ , known as ettringite ( $C_3A.(Cs)_3.H_{32}$ ) which reacts with  $C_3A$  to form 'monosulphate' as given below.

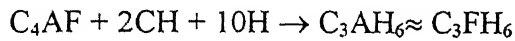


where  $C_3A.Cs.H_{12}$  is called monosulphate.

Pure calcium aluminate hydrate is not formed until there is no more sulphate from the mixing water or from the ettringite available to the tricalcium aluminate in the clinker grain. This hydration takes place via a number of intermediate stages, however it is assumed to yield the cubic  $C_3AH_6$ , neglecting the various intermediary reaction products.



The hydration of calcium aluminoferrites hydrates is expected to form  $C_3AH_6$  and different mixed oxide phases of similar structure where the aluminate is partially exchanged by ferrite.



All the above hydration reactions are exothermic in nature and an estimate of the total heat generated can be made on the basis of mineralogical composition of the cement i.e. the relative percentages of the different complexes, as explained below.

### 3.2 Concept of multi-component heat generation model

As far as the total heat liberation during the hydration of cement in any concrete is concerned it depends not only on the mineralogical composition of the cement used, as suggested above, but also on parameters like type of cement, cement content, water cement ratio, placing temperature etc.

To calculate the total heat generated, heat generation from each of the hydration reactions is calculated independently and is summed up to give the total heat of hydration.

#### 3.2.1 Parameters considered

The parameters considered for estimating the heat liberated during hydration concrete can be divided into two categories i.e. those relating to mix proportion and concrete

properties and the environmental factors, besides of course the characteristics of the cement used

The parameters relating to the mix proportion and properties of concrete are

1. Type of cement
2. Cement content
3. Water cement ratio
4. Activation energy of the individual clinker materials
5. and the environmental parameters are
6. Placing temperature of concrete
7. Ambient temperature
8. Wind velocity
9. Relative humidity

Depending on the temperatures of the individual constituents and the proportions of the concrete mix, fresh concrete has a placing temperature, which may be different from the ambient or environmental temperature, it is important to recognize that it is this temperature of the concrete that essentially governs the rate of hydration reaction and thus plays an important role in the rate and amount of heat liberation. The effect of wind velocity and relative humidity has not been considered in the present study.

### 3.2.2 Mathematical modeling of the heat liberated during hydration

In this study it has been assumed that the total heat liberation for cement  $H$  is the sum of the heat liberation of individual mineral compounds i.e.

$$H = \sum p_i H_i \quad (3.1)$$

where  $i$  represents the mineral particles ( $C_3A$ ,  $C_3S$ ,  $C_2S$ ,  $C_4AF$ , ettringite)

and  $p_i$  represents the weight percentage of the individual mineral compound. In other words,

$$H = p_{\text{mono}} H_{\text{mono}} + p_{\text{C3A}} H_{\text{C3A}} + p_{\text{C3S}} H_{\text{C3S}} + p_{\text{C2S}} H_{\text{C2S}} + p_{\text{C4AF}} H_{\text{C4AF}} \quad (3.2)$$

It may be noted that in the above equation,

$$p_{\text{mono}} + p_{\text{C3A}} + p_{\text{C3S}} + p_{\text{C2S}} + p_{\text{C4AF}} = 1.0 \quad (3.3)$$

and the first term represents the transformation of ettringite to monosulphate.

The individual  $H_i$  can be estimated on the basis of Arrhenius law as given below:

$$H_{i,T} = H_{i,T_0} \times \exp\{-E_i/R(1/T - 1/T_0)\} \quad (3.4)$$

where  $E_i$  is the activation energy of the  $i$ th component,  $R$  is the gas constant,  $T_0$  is the reference temperature (assumed as 293K in this case) and  $T$  is the temperature of concrete.

The referential heat generation rate, is dependent on many factors. In concrete the hydration is temperature path dependent so that  $H_{i,T_0}$  should be a function of accumulated heat generated by compound  $i$ . In addition it also depends on free water available and the thickness of cluster around non-hydrated clinker minerals. Thus,  $H_{i,T_0}$  can be written as

$$H_{i,T_0} = \beta_i \times F_i(Q_i) \quad (3.5)$$

here  $Q_i = \int H_i$

the function  $F_i$  represents the events occurrence in terms of accumulated heat as the indicator of the hydration level for individual component. The referential heat rate function obtained experimentally [11] for the various clinker minerals are given in Appendix B.

$\beta_i$  indicates the reduction in hydration rate with respect to the increasing thickness of cluster made of already hydrated product and the decreasing free water during hydration as

$$\beta_I = 1 - \exp\{-r (w_{\text{free}}/100\eta_I)^s\} \quad (3.6)$$

where  $\eta_I$  is the nondimensional indicator for cluster thickness around non hydrated particles made by already hydrated compounds and is given as

$$\eta_I = 1 - [1 - x_I]^{1/3} \quad (3.7)$$

$x_I$  is the degree of hydration at the time considered and is calculated by

$$x_I = \int Q_I / \int Q_{I,\infty} \quad (3.8)$$

$Q_{I,\infty}$  is the total heat generated by the compound I, during its complete hydration (kcal/kg)

Free water denoted by  $w_{\text{free}}$  is calculated by subtracting total amount of water consumed by hydration reactions from initial water contents. Coefficients  $r$  and  $s$  are material parameters.

Now, concrete may have different quantities of cement depending on the workability and/or strength requirements and thus different amount of heat could be liberated in the course of setting of a given volume of concrete.

The heat generation rate is given as

$$q = CH$$

where

$C$  is the cement content in the mix ( $\text{kg/m}^3$ ) and

$H$  is the specific heat rate of cement ( $\text{kcal/kg/hr}$ ) as estimated from equation 3.1 above.

Thus the formulation of the mixed cement heat generation model consists of some material parameters and constants. These values are given in Table-3.1 . The thermal activity potential of each mineral compound were obtained by conducting adiabatic temperature rise test and data processing by Kishi and Maekawa [11]. The coefficients  $r$  and  $s$  were identified based on the ordinary Portland cement.



**Table 3.1 Material parameters and constants for cement clinker minerals**

	C <sub>3</sub> A	C <sub>3</sub> S	C <sub>2</sub> S	C <sub>4</sub> AF	Ettringite
E/R	6500	6000	3000	3000	6000
r	2	2	2	2	2
s	2.5	2.5	2.5	2.5	2.5
JH	207	120	62	100	330

**3.2.3 Algorithm for the calculation of the heat of hydration***Given-**Mix proportion*

Type of cement used

Cement content

Water cement ratio

Activation energy of individual clinker minerals

*Environmental conditions*

Placing temperature

Ambient temperature

*Steps-*

Calculation of the amount of monosulphate in the mix

Calculation of the hydrated amount of clinker materials

Calculation of free water in the mix

Calculation of cluster thickness around the hydrated clinker materials (calculation of factor  $\eta_i$ )Calculation of factor  $\beta_I$  indicating the reduction in hydration rate due to increasing cluster thickness and decreasing free water

Assumption of referential heat function for various clinker materials

Calculation of the heat generated for the individual constituents of cement

Computation of the overall heat generation (Taken as the summation of heat generated for the various constituents)

### 3.3 Rise in temperature of concrete due to heat of hydration

If the heat generated in concrete due to hydration is not lost to the atmosphere, it could lead to substantial rise in the concrete temperature. Whether the heat is lost to the atmosphere or contributes to an increase in temperature depends on the factors including the geometry of the concrete member, atmospheric conditions etc. The effort in this study is directed

- (a) to estimate the adiabatic temperature rise of a concrete mass
- (b) to obtain the actual temperature distribution within concrete under different conditions of the atmosphere (assuming heat is lost to the atmosphere)

The details of the formulation are given below:

#### 3.3.1 Heat transfer analysis

The fundamental equation governing the distribution of temperature in a solid subjected to internal heat generation was given by Fourier as:

$$k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + w = \rho c \frac{\partial T}{\partial t} \quad (3.9)$$

where

$k$  is the conductivity coefficient

$c$  is the specific heat

$\rho$  is the mass density

$T$  is the temperature of the solid

In order to determine a unique solution to the Fourier equation adequate initial and boundary conditions should be given.

#### *Initial condition*

The initial condition must be defined by prescribing the temperature distribution throughout the body at time zero. That is,

$$T(x,y,z,t=0) = f(x,y,z) \quad (3.10)$$

#### *Boundary conditions*

Prescribed temperature boundary- The temperature existing on any boundary of the body must be given as

$$T(x,y,z,t) = f(x,y,z,t) \quad (3.11)$$

Conduction boundary condition- A prescribed heat flow boundary condition can be expressed as

$$k\partial T(x,y,z,t)/\partial n = q_n(x,y,z,t) \quad (3.12)$$

where  $q_n$  is the given amount of heat flow at point  $(x,y,z)$  and  $n$  is the outward normal to the surface.

Convection boundary condition- The rate of heat transfer across a boundary layer is given by:

$$k\partial T(x,y,z,t)/\partial n = h(T_e - T_s) \quad (3.13)$$

where  $h$  is the heat transfer coefficient,  $T_e$  is the known temperature of the external environment and  $T_s$  is the surface temperature of the solid.

Radiation boundary condition- Heat transfer by radiation between boundary condition surface and its surroundings can be expressed by:

$$q_r(x,y,z,t) = V\sigma \{ 1/(1/\epsilon_r + 1/\epsilon_s - 1.0) \} [T_r^4 - T_s^4] \quad (3.14)$$

where

$V$  is the radiation view factor

$\sigma$  the Stefan-Boltzmann constant

$\varepsilon_r$  the emissivity of the external radiation source

$\varepsilon_s$  the emissivity of the surface and

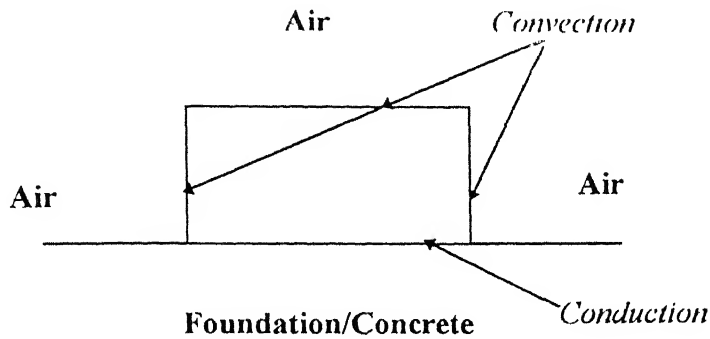
$T_r$  and  $T_s$  are the absolute temperature of the radiation source and the surface respectively.

### 3.3.2 Finite element formulation

The finite element method is a powerful tool in approximately solving thermal problems. The method is completely general with respect to geometry, material properties and arbitrary boundary conditions.

The various types of the blocks from the point of view of boundary conditions of heat transfer are explained in Chapter 1. Heat transfer analysis of the central blocks for the first layer of concreting has been done by the finite element method using the NISA package. The temperature rise distribution resulting due to the heat of hydration are evaluated wherein the heat of hydration is calculated by the multi-component model discussed before. The heat generation here is a function of both temperature and time and hence the heat transfer analysis type is the non-linear transient heat transfer analysis.

The size of the block has been taken to be 6m×3m×3m. In the model all thermal or heat transfer properties are assumed to be directional independent (isotropic material model). The block is taken to be infinite in one direction and a two dimensional heat transfer analysis has been done to evaluate the temperature rise distribution. The boundary conditions for the central block are as shown in Figure 3.1.



**Fig 3.1 Representation of boundary conditions of heat transfer for central blocks**

The element used for the modeling is the 2-D planar element for heat transfer which is based on the assumption of a 2-D state of heat flow. The element has the temperature as the only degree of freedom at each node. The temperature rise distribution for the block is obtained by the non-linear heat transfer analysis. The temperature profiles for the blocks depends on the following factors-

*Mix proportion*

Type of the cement

Cement content

Water cement ratio

*Environmental factors*

Placing temperature

Ambient temperature

*Boundary conditions for heat transfer*

Convection coefficient

Conduction coefficient

*Block size and placing intervals*

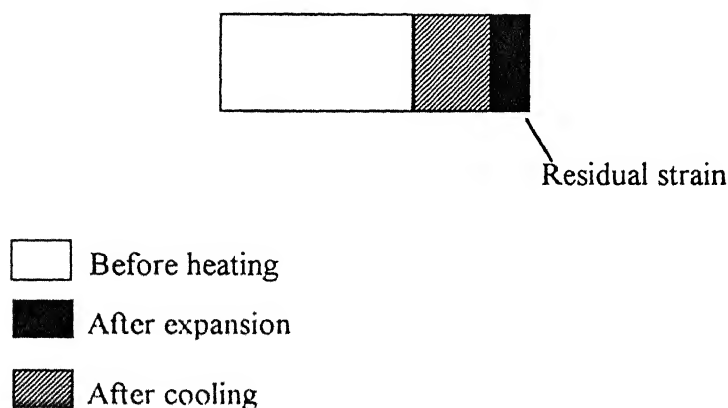
Lift thickness

### Time between various lifts

Due to the internal heat generation in the blocks the temperature of the blocks initially increases and reaches a peak temperature after which the cooling starts. Due to the cooling process there is contraction in the member which if restrained results in thermal strain in the member thus leading to the development of thermal stresses.

## 3.4 Development of thermal strain and stresses

It is clear from the discussion till now that there could be a substantial rise in temperature on account of liberation of heat during hydration of cement in concrete. However, once the hydration process approaches an end, the concrete seeks to cool to attain equilibrium with the atmospheric temperatures. This cooling is naturally accompanied by contraction, which is resisted due to internal and external restraint (as described below). The process is diagrammatically shown in Figure 3.2



**Fig 3.2 Representation of residual strain in concrete due to the heating and cooling**

As is clear from Figure 3.2 the cooled concrete has residual tensile strains which leads to the development of tensile stresses. Further it should be borne in mind that this process could be complete within about 8 to 10 days of casting and the concrete can be expected to have only nominal strength.

Thus, if the tensile stresses developed exceed the instantaneous strength, there is a strong likelihood of thermal crack formation. On the basis of the results obtained in the previous chapter concerning the amount of heat liberated and the peak temperature etc., an attempt has been made in this chapter to present a methodology for estimating the thermal stress developed, comparing them to the likely tensile strength (obtained using some of the existing models for strength development) and estimating the probability of cracking. The probability of thermal cracking is related to an index known as the thermal cracking index which is defined as the ratio of the instantaneous tensile strength of concrete to the maximum thermal stress developed.

### **3.4.1 Factors affecting thermal strain**

The factors affecting the calculation of thermal strain can be listed as follows,

Degree of restraint

Coefficient of thermal expansion

Difference in temperature between the peak temperature and the service temperature

#### **3.4.1.1 Degree of restraint**

All concrete elements are strained to some degree by volume because there is always some restraint provided either by the supporting elements or by different parts of element itself. Restrained volume change can induce tensile, compressive, or flexural stresses in the elements depending on the type of restraint and whether the change in volume is an increase or decrease. We are normally not concerned with restraint conditions which induce compressive stresses in concrete because of the ability of concrete to withstand compression. We are primarily concerned with the restraint conditions which induce

In the following discussion the types of restraint to be considered are external restraint and internal restraint.

### *External restraint*

External restraint exists along the contact surface of concrete and any material against which the concrete has been cast. The degree of restraint depends primarily on the relative dimensions, strength, and modulus of elasticity of the concrete and the restraining material.

By definition, the stress at any point in an uncracked member is proportional to the strain in the concrete. The horizontal stress in a member continuously restrained at its base and subject to an otherwise uniform horizontal length change varies from point to point in accordance with the variation in the degree of restraint throughout the member. The distribution of restraint varies with the length to height ratio ( $L/H$ ) of the member.

According to ACI 207.2R-11 following equations are given for the calculation of the degree of restraint-

For  $L/H$  equal to or greater than 2.5, restraint  $K_R$  at any point may be approximated by

$$K_R = [(L/H - 2.0)(L/H + 1.0)]^{0.11} \quad (3.15)$$

For  $L/H$  less than 2.5 restraint  $K_R$  at any point can be approximated by

$$K_R = [(L/H - 1.0)(L/H + 10.0)]^{0.11} \quad (3.16)$$

### *Internal restraint*

Internal restraint depends on the differential volume change within a member. Its effects add algebraically to the effects of external restraint, except that their summation will never exceed the effects of 100 percent external restraint. Therefore, where high external restraint conditions exist the effects of internal restraint may be negligible.



In the present work, knowing the size of the block the degree of restraint at any point is calculated by using the above equations for the external restraint condition, the effects of internal restraint are considered to be negligible.

#### 3.4.1.2 Coefficient of thermal expansion

The coefficient of thermal expansion depends on the type of aggregate used. The reported values of linear coefficient of thermal expansion for concrete mixtures of different aggregate types are 18, 12, and  $6-12 \times 10^{-6}$  per  $^{\circ}\text{C}$ . Here a value of  $12 \times 10^{-6}$  is assumed for the calculation of the thermal strains and stresses.

#### 3.4.1.3 Temperature change ( $\Delta T$ )

The change in temperature to be used for the calculation of thermal strain and stresses is given as the difference between the peak temperature obtained from the heat transfer analysis of the blocks and the service temperature.

Thus, after the calculation of the degree of restraint, the coefficient of thermal expansion and the temperature change, the thermal strain can be calculated by the equation

$$\varepsilon = K_R \times \alpha \times \Delta T \quad (3.17)$$

where

$K_R$  is the degree of restraint

$\alpha$  is the linear coefficient for thermal expansion and

$\Delta T$  is the temperature change between the peak temperature and the service temperature.

### 3.4.2 Thermal stresses

Since the magnitude of thermal stress is determined by the temperature gradient and the ratio of stiffness between the restraining body and the restrained body, it is necessary to evaluate the effective Young's modulus of hardening concrete.

#### 3.4.2.1 Calculation of Young's modulus

Young's modulus of concrete gradually increases with age, which is also influenced by the mix proportion. For the calculation of the Young's modulus of hardening concrete JSCE SP-2 gives the following equations-

$$E(t) = 1.1 \times 10^4 \sqrt{f_c(t)} \quad (\text{for upto age of 3 days}) \quad (3.18)$$

$$E(t) = 1.5 \times 10^4 \sqrt{f_c(t)} \quad (\text{for age more than 3 days}) \quad (3.19)$$

where  $E(t)$  is the effective Young's modulus at an age of  $t$  days, in  $\text{kgf/cm}^2$  and  $f_c(t)$  is the estimated compressive strength of concrete at an age of  $t$  days in  $\text{kgf/cm}^2$

The calculation of Young's modulus at any age is done using the above equations. The thermal stress is given as the product of thermal strain and the Young's modulus which is calculated as above. Thus,

$$\sigma = E \times \epsilon \quad (3.21)$$

which can be written as

$$\sigma = E \times K_R \times \alpha \times \Delta T \quad (3.22)$$

where

$E$  is the Young's modulus of elasticity

$K_R$  is the degree of restraint

$\alpha$  is the coefficient of linear thermal expansion and

$\Delta T$  is the change in temperature.

### 3.5 Tensile strength of concrete

The tensile stresses developed due to thermal strain can lead to cracking if their values exceed the value of tensile strength of concrete at that age. Thus to estimate the probability of thermal crack occurrence the tensile strength of concrete has to be accurately predicted.

The tensile strength of concrete is influenced by factors like type of the cement to be used, water cement ratio, kind of aggregates, temperature history and age. However an approximate value of the tensile strength may be obtained by the following equations as given by JSCE SP-2

$$f_c(t) = [t/(a+b \times t)] \times f_c(91) \quad (3.23)$$

$$f_t(t) = c \sqrt{f_c(t)} \quad (3.24)$$

where

$f_c(t)$  is the compressive strength of concrete at an age of  $t$  days, in  $\text{Kgf/cm}^2$

$f_t(t)$  is the tensile strength of concrete at an age of  $t$  days, in  $\text{Kgf/cm}^2$

$f_c(91)$  is the compressive strength of concrete at an age of 91 days, in  $\text{Kgf/cm}^2$

$a$  and  $b$  are the values as given in Table 2.1 before which are used in the standard practice and  $c$  is taken as 1.4 in standard practice, though it varies with such factors as degree of drying of concrete.

### 3.6 Evaluation of thermal cracking

A comparison between the maximum thermal stress developed and the tensile strength of concrete can be a measure of the probability of thermal crack occurrence.

To estimate thermal cracking JSCE has defined a parameter termed as thermal cracking index. The thermal cracking index is calculated as the ratio of the tensile strength of concrete to the maximum thermal stress developed as shown in principle by the equation-

$$CI = f_t / \sigma_t \quad (3.25)$$

where  $\sigma_t$  is the maximum thermal stress in tension to occur due to the heat of hydration and  $f_t$  is the tensile strength of concrete at the time of calculation of  $\sigma_t$ .

The larger the thermal cracking index, the lesser is the possibility of crack occurrence, and vice-versa. Generally, as the index becomes smaller, the number of cracks increases and the crack width tends to go larger.

The relationship between the occurrence of thermal cracks and the thermal cracking index has been documented in JSCE SP-2 which is based on several experiments and observation records during actual construction.

For reference, the standard values of the thermal cracking index are shown as follows:

- 1.5 and above : when cracking is to be prevented
- 1.2 to 1.4 : when the width and number of cracks are to be controlled while allowing cracking
- 0.7 to 1.1 : when not applicable to the above two

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## Chapter 4

### Results and Discussion

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#### 4.1 General

The results of the present work can be discussed under three categories. The first category deals with the results of the model developed for calculating the heat of hydration of cement in concrete. The second category is related to the results of the heat transfer analysis using the multi-component heat generation model developed in the present study

The third category discusses about the thermal stresses developed on account of thermal strain and about the evaluation of thermal cracking.

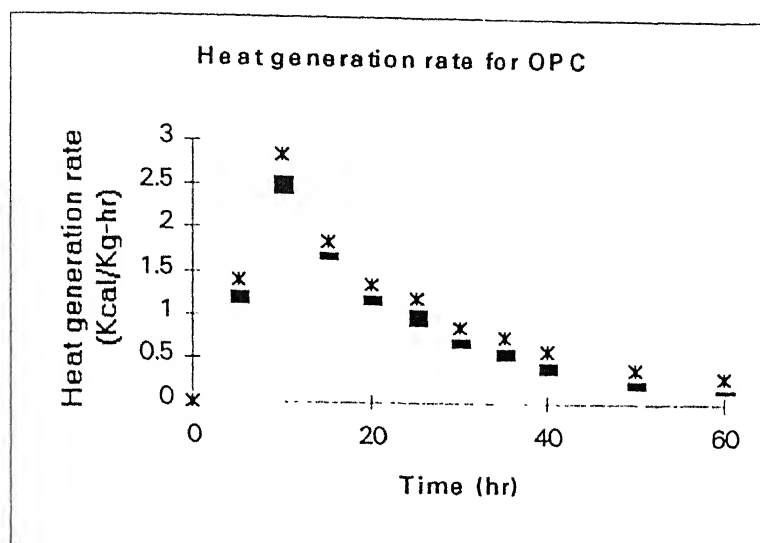
The input or independent parameters used in the study have been divided into those related to concrete and those related to the environment. Whereas water cement ratio, cement content, type of cement belongs to the former, placement temperature, ambient temperature are related to the latter. The effect of chemical and mineral admixture is not considered in the present study.

#### 4.2 Heat generation rate

The heat generation rate for cement depends on the cement composition, water cement ratio and the placing temperature of concrete.

The heat generation rate for ordinary Portland cement (Type-1) for a placing temperature of 20°C and a water cement ratio of 0.5 is given in Figure 4.1.

The calorimetric experimental heat liberation curve [12] for the same is also indicated on the same figure.



■ - Exp. data

\*- Present model

**Figure 4.1 Heat generation rate for ordinary Portland cement**

The heat generation rate increases in the beginning, reaches a maximum value and then tends to decrease and after a certain time it becomes zero.

### 4.3 Effect of cement composition on heat of hydration

To evaluate the effect of cement composition on heat of hydration, the heat of hydration values at different ages have been calculated for cement composition representing the average values for the ASTM type 1,2,3,4 and 5 compositions used in the classical work on heat of hydration by Verback and Foster.

The resulting values are compared with the experimental values of Verback and Foster. The chemical composition of cement types used is as shown below in Table 4.1.

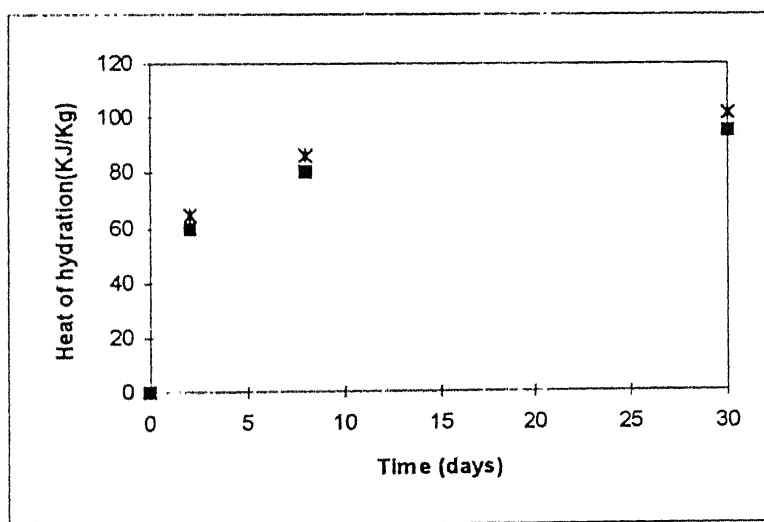
**Table- 4.1 Mineral composition of the various cement types**

Mix type	$C_3S\%$	$C_2S\%$	$C_3A\%$	$C_4AF\%$
Type- 1	49	25	12	8
Type- 2	45	30	6	8
Type- 3	56	15	12	8
Type- 4	30	46	5	13
Type- 5	45	30	2	15

The experimental values and the values obtained from the present model for the heat of hydration for the various cement types is as shown below in Table 4.2.

**Table-4.2 Heat of hydration for various cement types**

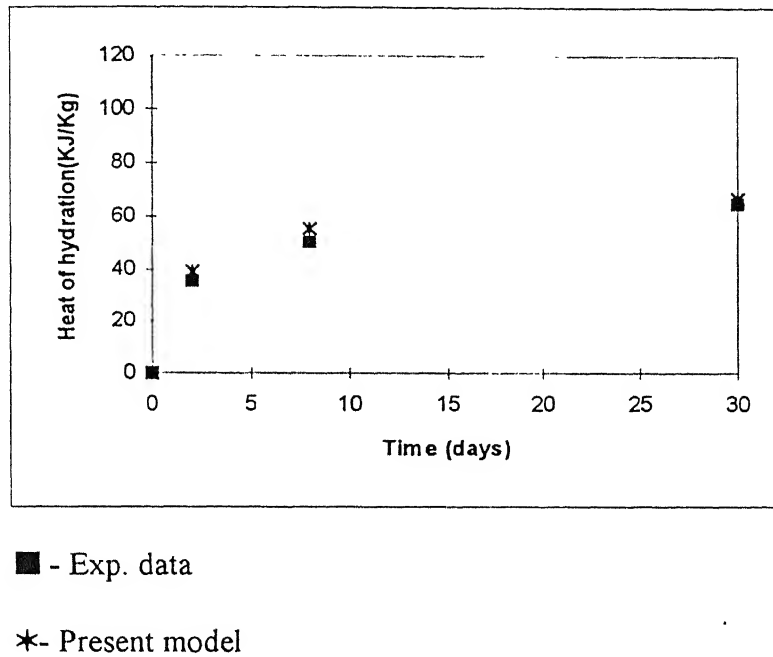
Time (days)	Type-1 (kJ/kg)		Type-2 (kJ/kg)		Type-5 (kJ/kg)		Type-4 (kJ/kg)	
	Exp.	Model	Exp.	Model	Exp.	Model	Exp.	Model
0	0	0	0	0	0	0	0	0
2	60	64.97	47	51.94	41	43.76	35	38.87
8	80	85.78	60	65.76	55	58.93	50	54.98
30	95	101.54	80	87.39	74	78.34	65	67.32



■ - Exp. data

\*- Present model

**Figure 4.2 Comparison of experimental and model results for heat of hydration of type-I cement**



**Figure 4.3 Comparison of experimental and model results for heat of hydration of type-IV cement**

As can be seen from the above Table the heat developed due to hydration at any age is maximum for the type-1 cement and is lowest for type-4 cement which was expected as the type-4 cement is defined as the low heat cement in which there are lesser amounts of  $C_3A$  and  $C_3S$  contents which have a major contribution to the heat of hydration.

#### 4.4 Effect of placement temperature on the heat of hydration

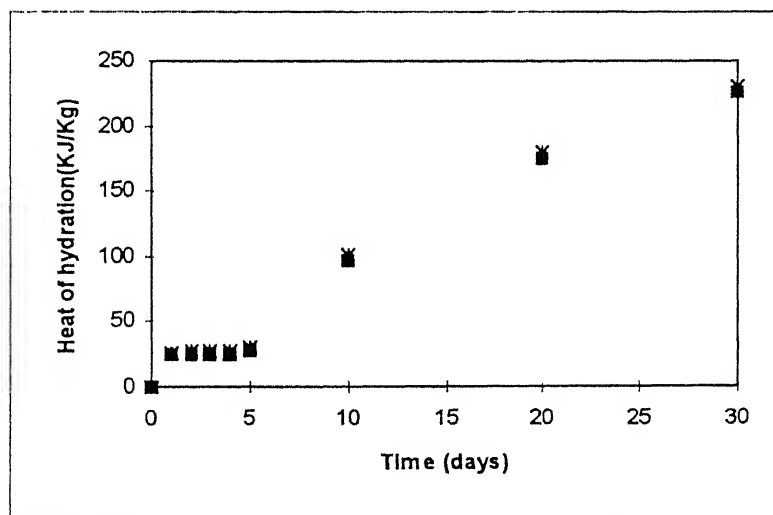
The effect of placing temperature on the heat of hydration is shown in Table-4.3. The cement type used for this study is the type-1 cement, the composition for which is given in Table 4.1.

The water cement ratio was taken to be 40% and the placement temperature was varied from  $20^{\circ}C$ - $60^{\circ}C$ . The results along with the experimental results obtained from Beton-Bogen, Aalborg cement company, Denmark [2] are shown.



**Table-4.3 Effect of placing temperature on heat of hydration**

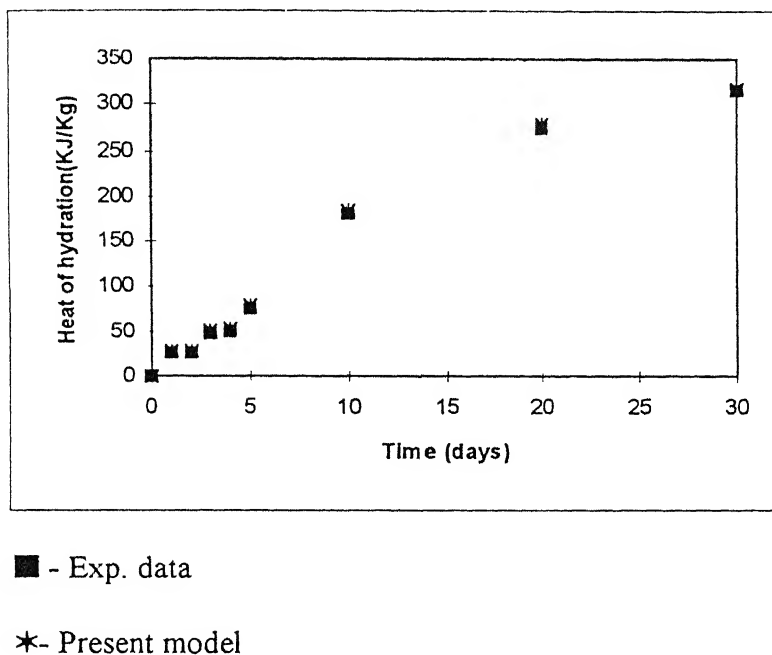
Time (days)	Placing temperature							
	20°C		30°C		40°C		60°C	
	Exp.	Model	Exp.	Model	Exp.	Model	Exp.	Model
0	0	0	0	0	0	0	0	0
1	25	26.64	25	26.84	25	26.92	25	27.15
2	25	27.86	25	27.95	25	28.86	28	29.56
3	25	28.00	25	28.46	47	50.76	128	131.74
4	25	28.12	27	29.67	50	54.23	148	152.58
5	27	31.38	50	55.74	75	79.65	180	184.56
10	97	100.65	125	129.65	180	184.34	280	285.98
20	175	179.54	225	229.54	275	279.65	310	314.76
30	225	230.73	275	279.65	315	318.06	370	376.08



■ - Exp. data

\*- Present model

**Figure 4.4.1 Comparison of experimental and model results for heat of hydration for placing temperature of 20°C**



**Figure 4.4.2 Comparison of experimental and model results for heat of hydration for placing temperature of 40°C**

As can be seen with the increase in the placement temperature the difference in the hydration heat is not significant in the early ages but is quite significant for the later period. Lower is the placing temperature, lower is the corresponding heat of hydration and hence lower is the temperature rise. Thus reducing the placing temperature can be an effective measure to control the temperature rise in concrete on account of the hydration process.

#### 4.5 Temperature rise on account of hydration heat

The temperature rise in concrete on account of the heat developed due to hydration of cement is studied for the following two conditions:

Adiabatic condition wherein there is no loss of heat

Loss of heat due to phenomenon like conduction, convection etc are considered.

### 4.5.1 Adiabatic temperature rise

In mass concrete the adiabatic temperature rise is of much interest. The adiabatic temperature rise is a function of the cement type, cement content, placing temperature and fineness of cement. In this study the effect of fineness of cement is not taken into account. The variation in the temperature profiles with all the other parameters is as shown below.

#### 4.5.1.1 Effect of cement type on adiabatic temperature rise

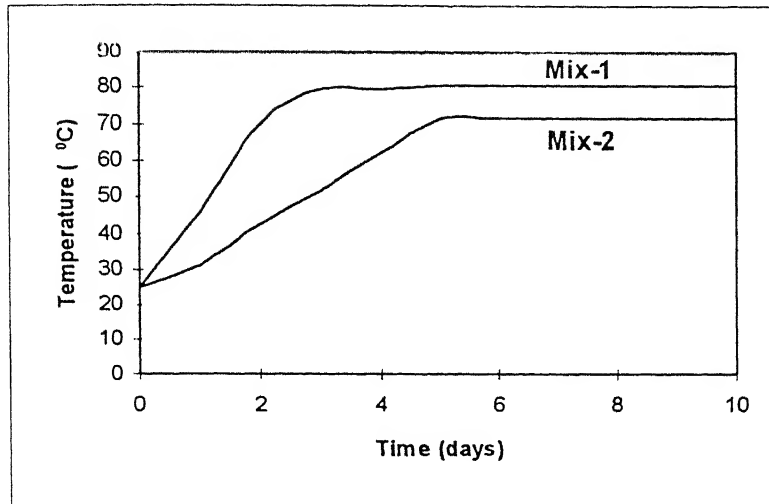
To study the effect of cement type on adiabatic temperature rise two concrete mix design of pure ordinary Portland cement (Mix-1) and moderate heat Portland cement (Mix-2) are considered. Table 4.3 gives the details of the cement composition of the two types used.

**Table 4.4 Composition of ordinary and mild heat Portland cements**

Type	$C_3A\%$	$C_3S\%$	$C_2S\%$	$C_4AF\%$	$SO_3\%$
OPC	10.4	47.2	27.0	9.4	1.85
MHPC	3.7	44.36	33.71	12.5	1.85

The cement content is taken to be  $400\text{Kg/m}^3$  and the water cement ratio is 0.39. The placing temperature of concrete is taken as  $25^\circ\text{C}$ . The results are as shown in Figure

4.5.1

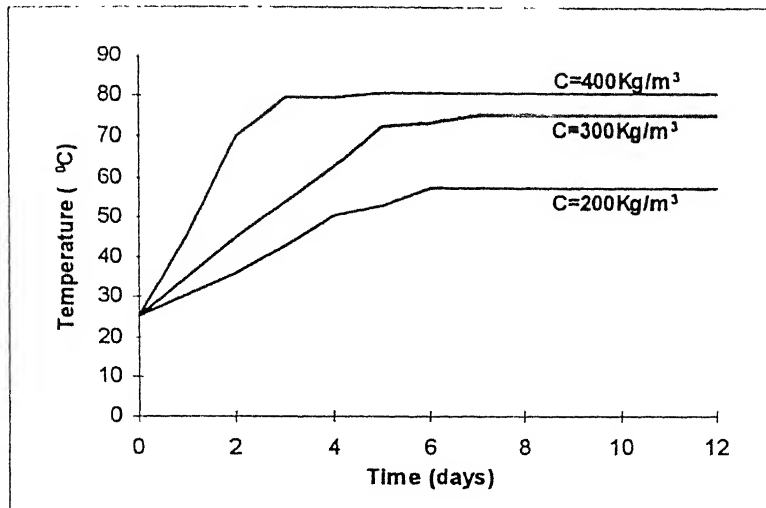


**Figure 4.5.1 Effect of cement type on adiabatic temperature rise**

As can be seen the final temperature reached for Mix-1 with ordinary Portland cement is much higher than that for Mix-2 with mild heat cement. This indicates that using a low heat type of cement can effectively reduce the peak temperature.

#### ***4.5.1.2 Effect of cement content on adiabatic temperature rise***

Codes often specifies a limit on the cement content as it affects the hydration process, the amount of heat liberated due to hydration thereby affecting the temperature rise distribution. To evaluate the effect of cement content on the adiabatic temperature rise three different cement contents of 200 Kg/m<sup>3</sup>, 300 Kg/m<sup>3</sup> and 400 Kg/m<sup>3</sup> at a water cement ratio of 0.39 and a placing temperature of 25°C are taken.

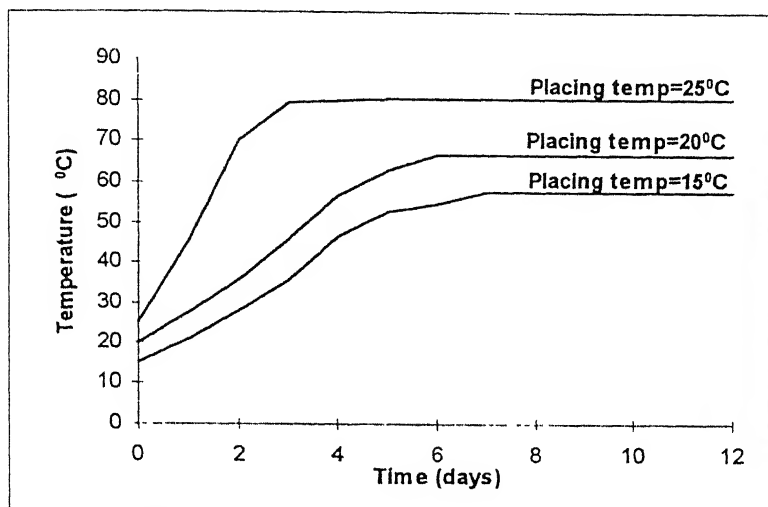


**Figure 4.5.2 Effect of cement content on adiabatic temperature rise**

When the water content does not get critical, the final temperature rise becomes proportional to the cement contents. As the cement content increases, the peak temperatures also tend to increase as can be seen from Figure 4.5.2

#### ***4.5.1.3 Effect of placing temperature on adiabatic temperature rise***

The placing temperature of concrete has considerable effect on the adiabatic temperature rise distribution. The effect of placing temperature is studied here with three placing temperatures of 15°C, 20°C and 25°C with a cement content of 400Kg/m³ and water cement ratio of 0.39.



**Figure 4.5.3 Effect of placing temperature on adiabatic temperature rise**

As is clear from the Figure 4.5.3 the maximum temperature reached increases with the placing temperature. Thus, reducing the placing temperature can reduce the peak temperature considerably.

#### 4.5.2 Temperature rise considering the heat losses

The temperature profiles for the central blocks are obtained by the heat transfer analysis taking into account the heat losses due to conduction and convection. The mix proportion used for the parametric study is as shown in Table 4.5

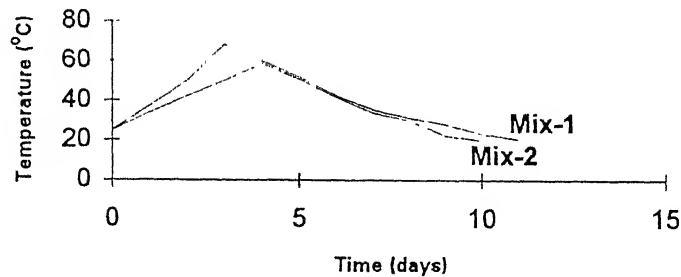
**Table 4.5 Mix proportions for obtaining temperature rise considering heat losses**

Mix	Cement type	Cement content (Kg/m <sup>3</sup> )	Water cement ratio
Mix-1	Type-1	300	0.49
Mix-2	Type-4	300	0.49

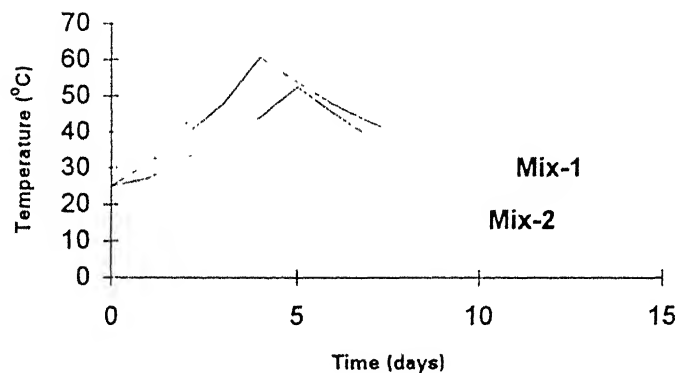
##### 4.5.2.1 Effect of cement type on temperature rise

The variation in temperature profiles with the two types of cement is as shown in

Figure 4 7(a) and (b). The placing temperature is taken as 25°C and the lift thickness for the block is taken as 3m and 1.5m.



**Figure 4.6 (a) Temperature rise versus time for 3m lift thickness**



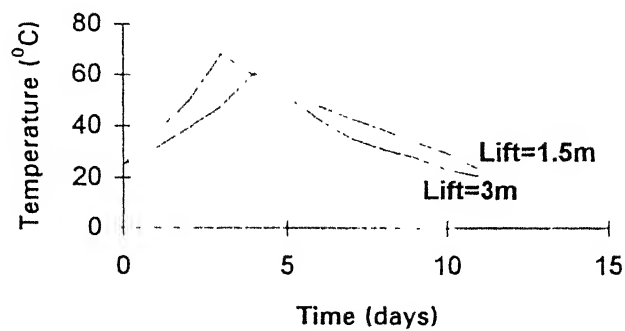
**Figure 4.6 (b) Temperature rise versus time for 1.5m lift thickness**

Mix-2 consists of low heat cement and hence the peak temperature is much lower than that of mix-1 which has the type-1 cement. Also the time at which peak temperature is attained is much delayed for mix.-2 in comparison to the mix-1.

#### 4.5.2.2 Effect of lift thickness on temperature rise

Reducing the lift height lowers the peak temperature reached on account of the heat

developed due to hydration. Figure 4.7 shows the peak temperature variation for two lift thickness of 3m and 1.5m. Mix-1 is considered for the study and the placing temperature is taken to be 25°C.



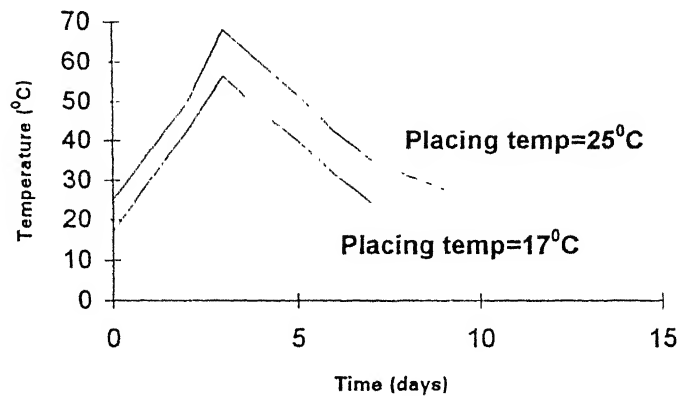
**Figure 4.7 Effect of lift thickness on temperature rise**

As can be seen from the above figure, reduction in the lift height leads to a reduced peak temperature. Also, the time at which the peak temperature is reached is also delayed with the reduction in the lift height.

#### ***4.5.2.3 Effect of placing temperature on temperature rise***

To study the effect of placing temperature on temperature rise, mix-1 is considered here which has the type-1 cement. The temperature rise for the placing temperatures of 25°C and 17°C is as shown below in Figure 4.8.





**Figure 4.8 Effect of placing temperature on temperature rise**

It can be seen above that lower is the placing temperature, lower is the peak temperature reached. Thus lowering the placing temperature by some artificial means such as precooling of aggregates can be an important measure so as to control the temperature rise in mass concrete.

#### **4.6 Estimation of thermal stresses, tensile strength of concrete and thermal cracking index.**

Using the results of the heat transfer analysis for the temperature rise distribution the modulus of elasticity, tensile strength, thermal stresses developed and thermal cracking index for concrete are evaluated. The peak temperatures obtained from the heat transfer analysis is used for the calculation of the thermal strain where the difference between the peak temperature and the service temperature is required. The time at which this peak temperature is reached is required for the calculation of tensile strength of concrete and the Young's modulus of concrete.

The peak temperatures and the time required to attain this temperature for the two placing temperatures of 25°C and 17°C are tabulated in Tables 4.6(a) and (b).

**Table 4.6(a) Peak temperature and time at peak for 25°C placing temperature**

Lift height (m)	Mix-1		Mix-2	
	Peak temperature (°C)	Time at peak temperature (days)	Peak temperature (°C)	Time at peak temperature (days)
3	68.27	3	58.36	4
1.5	60.76	4	52.69	5

**Table-4.6(b) Peak temperature and time at peak for 17°C placing temperature**

Lift height (m)	Mix-1		Mix-2	
	Peak temperature (°C)	Time at peak temperature (days)	Peak temperature (°C)	Time at peak temperature (days)
3	56.67	3	42.66	4
1.5	49.54	5	38.77	5

For the calculation of the thermal stresses the degree of restraint is calculated using the approximate equations as given in ACI recommendations for mass concrete. The tensile strength of concrete and the Young's modulus of elasticity are calculated using the approximate equations as given in JSCE SP-2. The results for the tensile stresses, tensile strength etc are given in Table 4.6(c) and (d).

**Table 4.6(c) Evaluation of thermal stress and thermal cracking index for 25°C placing temperature**

Mix type	Lift height (m)	Peak temp. (°C)	Time at which peak occurs (days)	Modulus of elasticity ( $1 \times 10^4$ MPa)	Tensile stress (MPa)	Tensile strength of concrete (MPa)	Thermal cracking index
Mix-1	3	68.27	3	1.2766	1.47332	1.67	1.133
Mix-2	3	58.36	4	1.89164	1.1358	1.7655	1.5543
Mix-1	1.5	60.76	4	1.89164	1.0146	1.7655	1.739
Mix-2	1.5	52.69	5	2.033	0.83210	1.8698	2.2471

**Table 4.6(d) Evaluation of thermal stress and thermal cracking index for 17°C placing temperature**

<i>Mix type</i>	<i>Lift height (m)</i>	<i>Peak temp. (°C)</i>	<i>Time at which peak occurs (days)</i>	<i>Modulus of elasticity (<math>1 \times 10^4</math> MPa)</i>	<i>Tensile stress (MPa)</i>	<i>Tensile strength of concrete (MPa)</i>	<i>Thermal cracking index</i>
Mix-1	3	56.67	3	1.2766	0.91159	1.67	1.83
Mix-2	3	42.66	4	1.89164	0.8737	1.7655	2.0207
Mix-1	1.5	49.54	5	2.033	0.905	1.8698	2.066
Mix-2	1.5	38.77	5	2.033	0.654	1.8698	2.858

The effect of various parameters like the cement type, lift thickness, placing temperature on thermal stress development and thermal cracking can be clearly seen above. As can be seen above the maximum thermal stress developed in each of the cases discussed above is less than the tensile strength of concrete at that age hence there will be no thermal cracking.

According to the JSCE SP-2 specifications considering the relationship between the thermal cracking index and the probability of thermal crack occurrence, larger is the thermal cracking index lesser is the probability of thermal cracking.

It is clear from above that mix-2 which consists of low heat cement has a larger value of thermal cracking index in comparison to mix-1 for both the lift thickness and hence has much less probability of cracking.

Similarly, it can be concluded from above that lesser is the lift thickness larger is the value of thermal cracking index and hence lesser is the probability of thermal crack occurrence.

#### 4.7 Concluding remarks

In the present chapter effect of both material and environmental parameters is discussed on the heat of hydration and all the related aspects. Variation of any of these parameters

affects the heat of hydration, temperature rise, thermal strain, Young's modulus thermal stresses, tensile strength of concrete and the thermal cracking index.

Depending on the value of thermal stresses, tensile strength of concrete, thermal cracking index etc. appropriate measures can be taken so as to reduce thermal cracking in mass concrete.

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# CHAPTER 5

## Conclusions

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### 5.1 Conclusions

A model has been developed for prediction of the heat generated and the temperature rise in mass concrete structures cast in large blocks.

The model uses concepts in cement chemistry and numerical heat transfer and takes into account parameters like the chemical composition of cement, proportions of concrete mix, geometry of the concrete block, temperature of fresh concrete, etc. The results can be useful in giving quantitative information on the extent of effect of these parameters like total heat generated, the maximum temperature reached.

A successful effort has also been made to study the probability of cracking on account of thermal stresses by comparing the maximum stress developed with the instantaneous tensile strength of the concrete.

## 5.2 Scope for future work

The work presented in this thesis can be further refined by

- Studying the effect of various parameters on the temperature profiles, thermal stresses etc. for the blocks of intermediate layers
- Taking into account the variation of ambient temperature with time in the heat transfer analysis.
- Considering the effect of mineral and chemical admixtures on the heat of hydration and the related aspects
- Taking into account the effect of forced convection caused by wind in the heat transfer analysis of the mass concrete blocks.
- Studying the effect of the type of formwork on the temperature fields resulting from heat of hydration.

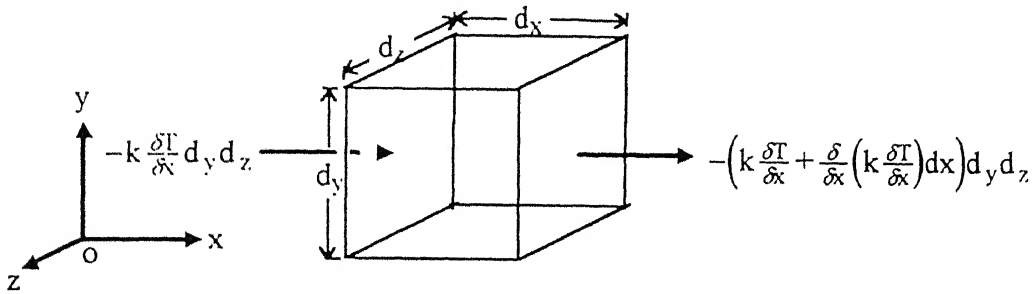
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## Appendix A

### Heat Transfer Analysis

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The fundamental equation governing the distribution of temperature in a solid subjected to internal heat generation was developed by Fourier. Consider a parallelepiped representing a volumetric element of a material, with conductivity coefficient  $k$ .



The change in heat flux in the x-direction is given by the equation:

$$\delta / \partial x (k \delta T / \delta x) dx dy dz$$

where,

$T$  is the temperature.

Similarly for y and z direction

$$\delta / \partial y (k \delta T / \delta y) dx dy dz \text{ and}$$

$$\delta / \partial z (k \delta T / \delta z) dx dy dz$$

Addition of the flux variation in the three directions, determines the amount of heat introduced in the interior of the element per unit time:

$$\{ \delta / \partial x (k \delta T / \delta x) + \delta / \partial y (k \delta T / \delta y) + \delta / \partial z (k \delta T / \delta z) \} dx dy dz$$

In the above derivation the material was considered to be isotropic.

Considering it also homogenous the above equation becomes :

$$k \{ \delta^2 T / \delta x^2 + \delta^2 T / \delta y^2 + \delta^2 T / \delta z^2 \} dx dy dz \quad (A.1)$$

For a material with mass density  $\rho$  and specific heat  $c$ , the increase of internal energy in the element is given by:

$$\rho c dx dy dz (\partial T / \partial t) \quad (A.2)$$

where  $t$  is the time.

When there is no heat generation in the material, then equating equation 1 and 2 we have

$$k \{ \delta^2 T / \delta x^2 + \delta^2 T / \delta y^2 + \delta^2 T / \delta z^2 \} = \rho c (\partial T / \partial t) \quad (A.3)$$

Equation A.3 can be rewritten as

$$\kappa \nabla^2 T = (\partial T / \partial t)$$

where,

$$\nabla^2 T = \delta^2 T / \delta x^2 + \delta^2 T / \delta y^2 + \delta^2 T / \delta z^2 \text{ and}$$

$$\kappa = k / c\rho = \text{thermal diffusivity}$$

Considering the case with heat generation inside the material, Equation A.1 when added to the quantity of heat generated in the interior of element per unit of time  $w dx dy dz$  can be equated with the increase of internal energy in the element. Therefore, the Fourier equation is obtained:

$$k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + w = \rho c \frac{\partial T}{\partial t} \quad (A.4)$$

In order to determine a unique solution to the Fourier equation adequate initial and boundary conditions should be given. Following are the initial and boundary conditions used in the heat transfer analysis.

#### *Initial condition*

The initial condition must be defined by prescribing the temperature distribution throughout the body at time zero. That is,



$$T(x,y,z,t=0) = f(x,y,z)$$

### *Boundary conditions*

Prescribed temperature boundary-The temperature existing on any boundary of the body must be given as

$$T(x,y,z,t) = f(x,y,z,t)$$

Conduction boundary condition-A prescribed heat flow boundary condition can be expressed as

$$k \partial T(x,y,z,t) / \partial n = q_n(x,y,z,t)$$

where  $q_n$  is the given amount of heat flow at point  $(x,y,z)$  and  $n$  is the outward normal to the surface.

Convection boundary condition- The rate of heat transfer across a boundary layer is given by:

$$k \partial T(x,y,z,t) / \partial n = h (T_e - T_s)$$

where  $h$  is the heat transfer coefficient,  $T_e$  is the known temperature of the external environment and  $T_s$  is the surface temperature of the solid.

Radiation boundary condition- Heat transfer by radiation between boundary condition surface and its surroundings can be expressed by:

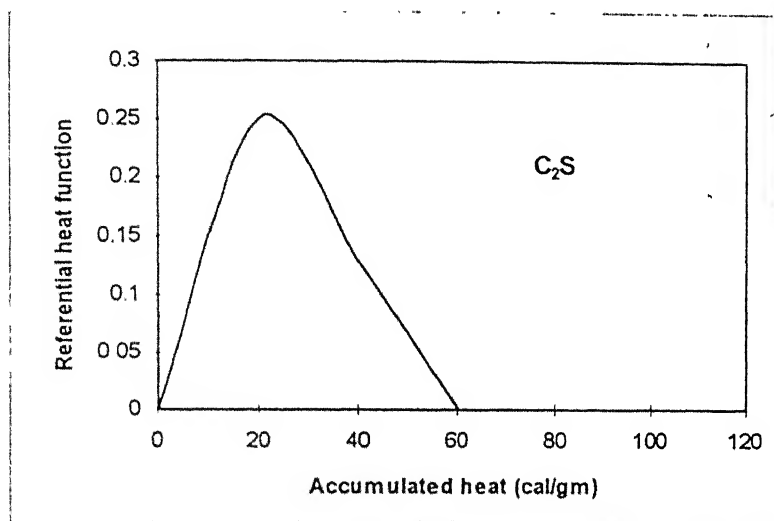
$$q_r(x,y,z,t) = V \sigma \{ 1 / (1/\epsilon_r + 1/\epsilon_s - 1.0) \} [T_r^4 - T_s^4]$$

where  $V$  is the radiation view factor,  $\sigma$  the Stefan-Boltzmann constant,  $\epsilon_r$  the emissivity of the external radiation source,  $\epsilon_s$  the emissivity of the surface, and  $T_r$  and  $T_s$  are the absolute temperature of the radiation source and the surface respectively.

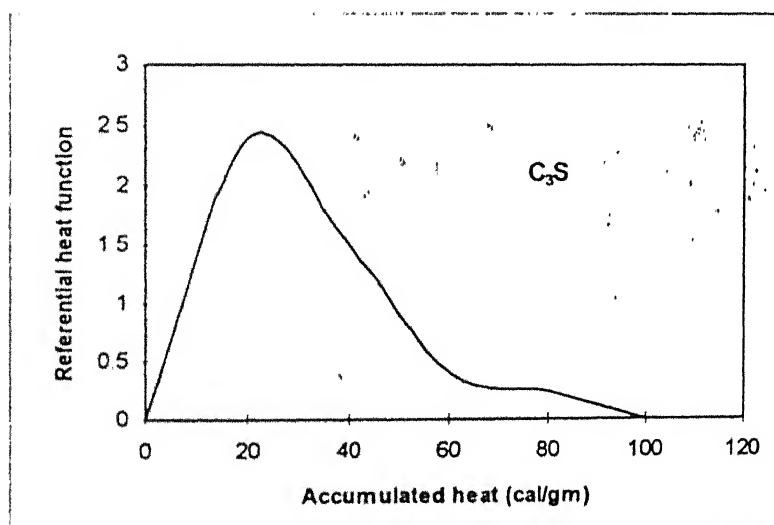
• • •

## Appendix B

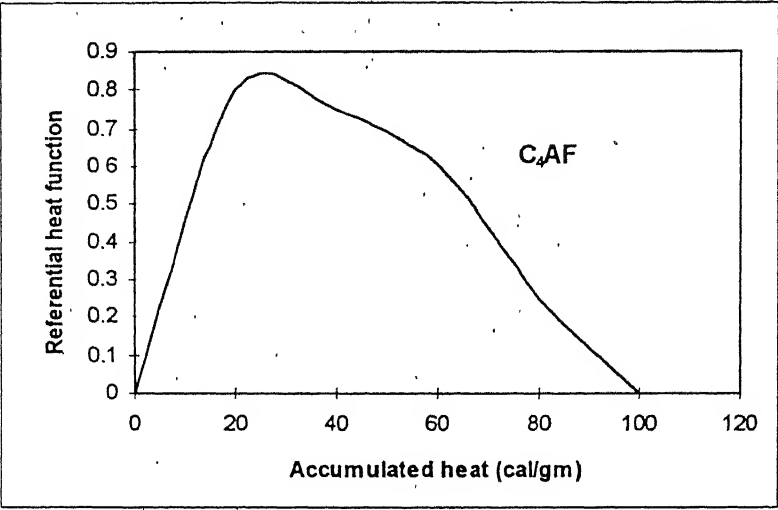
### Referential Heat Rate Function for Various Cement Clinker Minerals



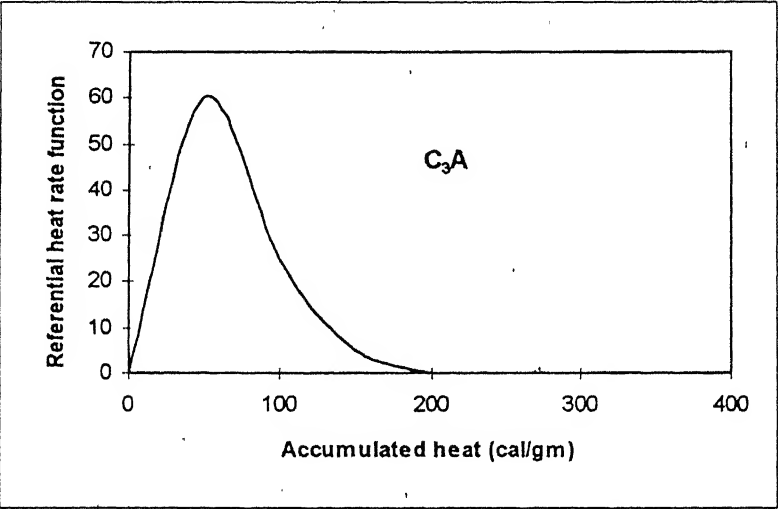
(a)



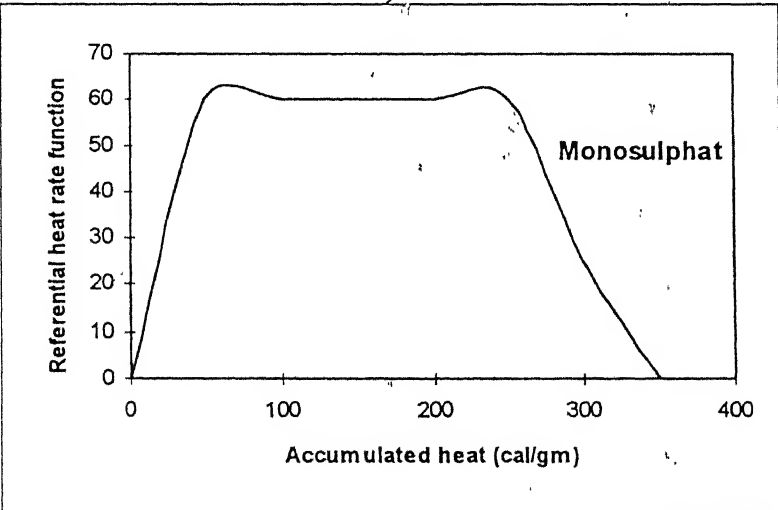
(b)



(c)



(d)



(e)

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